THE RELIABILITY AND VALIDITY DEVELOPMENT OF AN MSK PROFILING TOOL AND ITS VALUE IN YOUTH ATHELTES AND PROSPECTIVE INJURY RISK

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Glossary of Terms

ACJ	Acromion Clavicular Joint
ACL	Anterior Cruciate Ligament
ACLR	Anterior Cruciate Ligament Reconstruction
ADF	Ankle Dorsiflexion Angle
ASIS	Anterior Superior Iliac Spine
AUC	Area under the curve
CAI	Chronic Ankle Instability
DASH	Disabilities of the Arm, Shoulder and Hand Questionnaire
DF	Dorsiflexion
DKV	Dynamic Knee Valgus
FA	The Football Association
FAI	Femoral Acetabular Impingement
LESS	Landing Error Scoring System
FMS	Functional Movement Screen
FPPA	Frontal Plane Projection Angle
HADD	Hip Adduction Angle
HFA	Hip Flexion Angle
ICC	Intraclass Correlation Coefficients
IoC	International Olympic Committee
KFA	Knee Flexion Angle
IR	Internal Rotation
LCL	Lateral Collateral Ligament
LESS	Landing Error Scoring System
LL	Lower Limb
LTL	Lateral Trunk Lean
MCL	Medial Collateral Ligament
MDT	Multi-Disciplinary Team
MSK	Musculoskeletal
NCAA	National Collegiate Athletic Association
NFL	National Football League

NGBs	National Governing Bodies
NMC	Neuromuscular Control
NMST	Netball Movement Screening Tool
NWB	None-weight bearing
OA	Osteoarthritis
PEA	Percentage of Exact Agreement
PFJ	Patellofemoral Joint
PFP	Patellofemoral Pain
PFPS	Patellofemoral Pain Syndrome
PHV	Peak Height Velocity
QASLS	Qualitative Analysis of Single-leg Loading
RFU	The Rugby Football Union
ROC	Receiver Operating Characteristic
RTP	Return to Play
SABN	Shoulder Abduction
SDD	Smallest Detectable Difference
SEBT	Star Excursion Balance Test
SEM	Standard Error of Measurement
SEN	Shoulder Extension
SIMS	Soccer Injury Movement Screen
SLL	Single-leg Land
SLS	Single-leg Squat
TFA	Trunk Flexion Angle
TJA	Tuck Jump Assessment
TRIPP	Translating Research into Injury Prevention Practise
2D	Two- Dimensional
3D	Three – Dimensional
%PAH	Predicted Percentage of Adult Height

ABSTRACT

This work documents the development of a clinically feasible MSK qualitative profiling tool, and its subsequent application in adolescent athletes to improve profiling practise and the potential future impact of injury burden and incidence.

Research started by critically evaluating the literature to establish the current rationals, frameworks and models that underpin injury "screening" and profiling philosophies. Issues were identified around understanding of the injury problem beyond reductionist medical modelling to that of complex systems approaches, that were impacting contemporary profiling and injury prevention strategies. It was also identified that there were inherent limitations in general profiling practises, terminology and clinical utility of laboratory-based protocols that were non-transferable to real-world practise.

Therefore, nine 2D kinematic parameters and a compound and component qualitative scoring system was analysed to develop a methodological protocol, based on a holistic complex systems approach that had acceptable validity and reliability, but did not compromise on clinical utility. Significant correlations were found between the qualitative analysis and 2D kinematic measures at the trunk, hips and knees, along with moderate to excellent within and between session and intra-rater reliability. Indicating the QASLS tool is a valid and reliable field-based method of analysing movement quality, but recommendations included further refinement of statistical exploration and application into additional populations.

The following chapters built on the findings of the methodology and key learnings from the literature review to explore the application of the profiling tool in an adolescent population, where growth and maturation are a potential intricate driver to the movement quality complexity paradigm. Movement quality and performance of two unilateral loading tasks by and adolescent cohort demonstrated large movement variations with results suggesting that isolated evaluation of one kinematic parameter did not translate well into whole movement pattern evaluation, likely due to adolescent individual movement patterns being driven by numerous factors beyond one movement variable. Trends were observed between maturational groups with prepubertal athletes demonstrating greater variation and number

of movement strategies to complete the same unilateral tasks than circa-PHV athletes, and landing tasks overall demonstrating greater movement variation than squatting. This cross-sectional work was further explored through investigation of adolescent task performance longitudinally over the course of an academic year and sporting season. Single-leg squat performance did not appear to change over the course of a season regardless of maturational status, however unilateral landing performance did.

Whilst overall compound QASLS score reflected a downward trend in the number of deployed strategies with advancing maturation, changes in landing performance between the start and mid and mid to end of season was observed in those at 85-95 PAH% - the time associated with the growth spurt – and start to end of season differences were noted in those between >96-100 PAH%. Consequently, findings suggest that practitioners who implement profiling tools in an adolescent population include a maturational measurement alongside, and apply a tool at multiple points through a year or season, rather than as a stand-alone pre-season measure. This ensures capture of movement quality that is potentially impacted by the growth spurt, and a more contextual inference of results. Correspondingly, QASLS component selection to complete either unilateral task demonstrated relationships to PAH%, it is recommended practitioners are mindful that certain observed movement strategies maybe relative to a phase of growth and not necessarily indicative of an intervention or movement correction requirement. Exploration of calculation methods highlighted the limitations of diminished insight into an individual's movement bandwidth. This has important implications for the adolescent athlete that might be undergoing a natural change in their performance movement bandwidth.

Finally, an online education rater-training piece was developed to improve the overall inter-rater reliability of the QASLS tool for both the adult and adolescent populations. It is advised that rater training is completed in both specialist and none-specialist raters to improve levels of agreement and alignment to agreement of a criterion rater, to ensure the general robust application of the tool to improve profiling application and its utilisation overall.

Preface

In September 2017 I started this research process with an expectation of completing a prospective study on musculoskeletal (MSK) screening and profiling of the lower limb in relation to injury risk.

How wrong was I.

Bahr's group had recently released the editorial asserting that screening tests did not predict injury and probably never would (Bahr, 2016). Several limitations around relevant populations, appropriate statistical analysis and establishing stronger relationships between tools and injury risk were identified. Prior to the commencement of this research I worked as a physiotherapist in elite sport, having been involved in annual and bi-annual screening processes from academy level up to world class olympic programmes, I had definitely traversed that coalface of mass full day testing clutching a spreadsheet with 40 odd performance variables to be populated. And yet people were still getting injured in an unpredictable way. I had also witnessed first-hand the devastating effect sustaining an injury had on athletes at every level. In the younger age groups, the cessation of participation in the sport having both mental, physical and long-term health impacts. At the elite level it could cost that highly coveted podium medal winning spot, your career and financial means. I can understand why people are keen to prevent injury and its subsequent impact.

Prior to life in physio I had trained as a dancer, although due to my own injuries retired early (ironic). As a dancer you learn to understand multiple complex 3-D movement patterns physically and it is well understood there are many routes to the same outcome. Whilst movement patterns could be considered effortless or laborious in their quality, there was no inherently good or bad.

Within MSK practise there has been a long-standing relationship with quality of movement, with practitioners spending their professional lives encouraging people to move in some form or another. Contrary to my beliefs (that movement is just movement), it's clear that in the context of sport science and medicine movement quality was reduced into good and bad, and further subdivided into categories of risky or harmful. Dance and sport produce movement at the extreme, yet the perceptions of movement's potential impacts and relationships to injury between the two are polar opposites. How the same thing can be considered potentially detrimental in one environment, yet accepted as normal and none-problematic in another continues to fascinate me. This mismatch between acceptance of holistic intricacy, and reductionist view of identifying one singular performance metric, further confounds the complexity of the issue. Understanding the greater context was going to be a critical aspect of this piece. Subsequently a personal interest has developed in the gap that sits between academic and performance research, this observation lead to my pursuit of this research topic.

The literature review was a continuing process through this work that sought to inform about current rational, profiling tools and assessment tasks. Literature suggested that this wasn't a diagnostic problem it was a complexity problem. A highly complicated, human and performance web of interaction one at that. I've learnt from working in sport, to understand what is required and work backwards from there. Resultantly, the thesis is constructed in a reverse engineered way towards a prospective study. Sequential in its approach, each hypothesis has generated another, each building upon the previous stage, in an effort to move closer to a prospective study solution.

Chapter 3 summarises research into the validity, reliability (informed by the literature review, pilot data and practitioner required clinical utility), of the field-based methodology used throughout this study. Trying to address some of the feasibility issues with current gold standard movement analysis methods further highlighted the need of field-based tests. Capturing the real world couldn't currently happen in a lab. In an effort to fill the relevant population assessment gaps, chapter 4 utilises the qualitative tool developed in chapter 3 in a youth multisport population. As such, both chapters 3 and 4 continued to cross-sectionally develop the protocol established to further investigate the value of the complex systems approach to whole movement pattern evaluation.

To further support a paradigm shift from reductionist to complex longitudinal evaluation was considered key to use in any prospective injury study. This undoubtedly has its own set of challenges. Obtaining the numbers required for academic robustness, required multiple organisations and resulted in a multi-centre study. Recruitment and retention of multiple organisations is bloody hard. Changes in management and backroom staff resulted in organisations withdrawing study consent, as it no longer fit with the new philosophies. Collecting heights and weights-no matter how sensitively collected can be an emotive topic for some sporting national governing bodies (NGBs). Granting consent to the movement quality aspects, but not anthropometric elements (essential to maturational determinants) has resulted in tough conversations around participation for others.

Nor did I expect a global pandemic to be an academic problem.

Covid-19 impacted chapter 5 but unwittingly exposed the positive potential of the qualitative tool. Due to the move towards virtual life, organisations required solutions that could be completed digitally, in a socially distanced way. This further highlighted the versatility of the tool and the need to revisit rater-reliability.

For successful mainstream use profiling tools have to be adopted by multiple practitioners. Multiple practitioners allow multicentre collection, which provides greater participant numbers, and additional opportunities for relationship exploration between performance variables in injury risk. Informed by chapters 3 to 5, chapter 6 explores the effects of an educational piece on rater levels of agreement and consistency of use of the qualitative tool to explore the prospects of wider use. Whilst this was not the prospective study I had anticipated, I feel that this PhD provides a playbook guide of how to design and execute the prospective study I had envisaged. Hopefully to be continued by myself through postdoctoral work, or built upon by others in the sporting world.

Gemma Parry
October 2020.

Chapter One

1.0 Introduction

Musculoskeletal (MSK) screening most notably of the lower limb (LL) is a cornerstone of sports science medicine practise. It is utilised by practitioners across the wider sports science and clinical settings to identify movement restrictions through observation of patterns of movement within a group, team or individual, that may be suggestive of susceptibility to injury or potential pathology. The previous rational for use of a single movement or amalgamation of movements is to evaluate for proposed exposure, formulate an intervention to reduce or eradicate risk, resulting in application of an intervention to prevent occurrence.

Whilst single joint or biomechanical parameters evaluation has historically been the chosen method of analysis, there has been a distinct shift away from isolated approaches to that of an integrated evaluation of the whole movement pattern (Bennett *et al.*, 2017). Movement profiling tests are rapidly becoming embedded in clinical and sporting environments not only to evaluate risk but to dictate programming. Whilst practical application has been proliferate, the critical analysis and exploration of these tests against rigorous criterion measures, there reliability and validity, as well as the potential interactive relevance between prediction, prevention and intervention, remains relatively unexplored.

Along with a shift away from isolated methods of movement assessment, there have been paralleled shifts in injury prevention frameworks from reduced simplicity to that of multifactorial complexity (Van Mechelen, Hlobil and Kemper, 1992; Meeuwisse, 1994; Bittencourt *et al.*, 2016). Complexity comes with a level of uncertainty that is not commonplace within sports science research (Bittencourt *et al.*, 2016), but appears to be an emerging key component to further advancing deeper understandings around sports injury as a problem, and the procurement of effective and appropriate sports injury solutions.

Given the importance of movement quality to a successful return to sport, retaining participant engagement with sport, and the potential identification of predisposition in individuals. Proper evaluations of movement profiling tools, in both the clinical and field-based setting, is required. To ensure the accurate and consistent measurement of valid and reliable movement parameters, that are reflective of the inherent rate of change associated with human movement. This will help clinicians with the proper evaluation of movement quality, application of tools in practice with concise clarity, impactful application to rehabilitation, performance and return to play, and renewed interpretation of the literature regarding measurement error.

Injury as a whole is a complex, organic, continually evolving process that comprises many components and extensive multifactorial causes (Finch, 2006; Meeuwisse *et al.*, 2007; Bittencourt *et al.*, 2016; O'Brien *et al.*, 2019). Whilst several injury prevention frameworks have begun to examine the relationships and weighting of how these risk factors interact contextually (Bittencourt *et al.*, 2016; O'Brien *et al.*, 2019), the links of potential injury risk factors to injury is predominantly still unknown. This is further confounded by the methodological designs of intervention, or "injury prevention" research, that remains linear and monocausal, not only in its reporting but in its general approach. In consideration of this the thesis aims to offer an alternative approach to explore and deepen the understanding of injury, by acknowledging the recent advances regarding complex systems in injury prevention models and reconsidering the concepts of MSK profiling from a context driven approach.

Current research approaches to profiling and screening, generally tend to follow cross-sectional designs, and whilst these results offer thorough detailed analysis of risk-factors, it is important to be aware of the limitations of this study design approach. Within cross-sectional study designs, outcomes and exposure are simultaneously assessed, rendering the study unable to establish evidence of any relationship between exposure and outcome (Carlson, Sheehan and Boden, 2016). By omitting the inclusion of longitudinal data within most profiling research, it has remained significantly challenging to establish not only true cause and effect relationships between risk factors, but the contextual strength of any of those relationships. Which perpetually reinforces the wrongful predictive rationale. To further develop the practise of profiling, movement pattern changes will be evaluated over a training period or season to firstly establish if any changes that maybe linked to injury risk factors can be effectively identified, and to close the disparities between injury prevention frameworks, and injury prevention study design. The work will focus on the establishment of the reliability and validity of a new qualitative visual rating criteria that can evaluate multiple potential risk factors simultaneously, to a criterion two-dimensional (2D) measure, across two commonly employed unilateral movement tasks. Movement patterns, and there quality have also been described as injury risk factors within the adolescent athletic populations (Quatman-Yates *et al.*, 2012; Difiori *et al.*, 2014; Agresta *et al.*, 2017; Von Rosen, Heijne, *et al.*, 2018). Movement quality is of notable interest within sports science due to the growth spurt and potential changes within motor performance encountered by this population during growth and maturation (Quatman-Yates *et al.*, 2012; Difiori *et al.*, 2014; Cumming *et al.*, 2017). The physical changes between the muscular and skeletal systems encountered during growth, have led to the identification of growth and maturation as a specific problem and potential risk factor itself (Quatman-Yates *et al.*, 2012; Difiori *et al.*, 2014; Cumming *et al.*, 2017). Despite research regarding growth spurt related injuries remaining inconclusive.

Current profiling literature infers that injury risk factors are similar for youth athletes and the adult population. Distinct research investigating movement quality profiling specifically in a growing population, rather than just applying adult profiling principals that are potentially unsympathetic to a maturing cohort (Bolling *et al.*, 2018) remains scarce. Investigation into understanding changing movement quality encountered during adolescent growth and how it may be profiled is therefore warranted. Additionally, the thesis also aims to explore the value of the qualitative visual rating criteria in a youth population, with consideration given to maturation to try to further elude how the context of growth during adolescence impacts movement quality, potential risk factors and the sports injury problem. The value of context is considered the most important aspect of this body of research, the introduction provides an outline of the literature base relations to current injury prevention rationales, prevention models and frameworks and injury prevention strategies, that underpinned and informed the aims and potential research gaps to be answered by this thesis. Furthermore, current profiling tools and tasks will be presented, along with contemporary understanding of the implications for the adolescent athlete.

1.2 Trends in Injury Occurrence and why clinicians try to prevent injuries

Chronic Musculoskeletal conditions and injury, markedly that of the lower limb, are on the rise within the sporting and none-sporting populations (Squires *et al.*, 2012; Schurr *et al.*, 2017; Whittaker *et al.*, 2017). Whilst the cost of injury in sport at adult and adolescent levels is usually well documented, in terms of financial but also the additional implications such as time-loss player availability, and athlete development time loss, (Bahr, 2016; Rejeb *et al.*, 2017; Soligard *et al.*, 2017; Bahr, Clarsen and Ekstrand, 2018). The military and general populations - although less documented - are also susceptible. Musculoskeletal disorders are one of the primary causes of sickness absence in the workplace, which is estimated to currently cost the United Kingdom £20 billion and account for 3-4% of loss of worker time (Squires *et al.*, 2012). Musculoskeletal injuries account for around 20-59% of injuries within the British Armed Forces and are the leading cause of medical discharge (Sharma *et al.*, 2015). Within all of these populations, the most predominant recorded injuries are those within the lower limb, due to the socio-economic and health burden costs, as well as the impedance of sporting competitive success, there has been an ever-increasing shift in moving towards prevention of these injuries rather than just retrospective management.

1.3 Injuries to Lower Limb

It has been established that lower limb musculoskeletal injuries remain a significant problem within the elite and amateur athletic populations at both the adult and adolescent level, injury to the lower limb is calculated to comprise more than 50% of total injuries sustained in university-level athletes (Hootman, Dick and Agel, 2007). Albeit prevention and reduction being cited as a primal aim by most professional bodies and practitioners, many patients continue to suffer re-injuries. Prospective research has demonstrated that elite football players stood 2-3 times higher risk of reinjuring hamstring, groin or knee following previous injury (Hägglund, Waldén and Ekstrand, 2006) . Within the first two weeks following RTP, approximately one third of hamstring strains reoccur, resulting in significantly more time loss that the first (Erickson and Sherry, 2017) and additional injuries at other joints. With anterior cruciate ligament (ACL) reinjury rates in adolescent athletes at a minimum of 2 years post anterior cruciate ligament reconstruction (ACLR) recorded at 24.3%, with 5% of those also reporting subsequent none ACL related knee injuries (Fones *et al.*, 2020). Not only do athletes appear to sustain the same injury again, but they also appear susceptible to further injuries at additional joints.

1.3.1 Hip Complex

Injury to the hip joint is hugely complex and whilst accountable for 6% of all sports injuries can be hugely debilitating and account for the greatest amount of time lost during competition (Mather and Ferrell, 2018). Hip pain can frequently present as groin-pain and vice-versa as the two are not mutually inclusive or exclusive of each other but similar to the hip, groin pain is common in multi-directional sports and also complex to manage. Hip flexor and adductor strains are the most reported diagnosis, followed by intra-articular injuries (predominantly Femoral Acetabular Impingement – (FAI) accounting for a significant amount of time loss from sport (Mather and Ferrell, 2018; Thorborg *et al.*, 2018).

FAI is a range limiting pathology that attributes to dynamic impingement and altered movement patterns through the lumbar spine, sacroiliac and pubic symphysis. Frequently associated with delayed return to play (RTP) FAI also precedes early-onset hip osteoarthritis (OA) (Whittaker *et al.*, 2017). The majority of hip and groin-related injuries occur through overuse none-contact mechanisms such as change of direction, skating, high-intensity kicking and movements that generally involve forceful repetitive motion. All modifiable factors that can, therefore, be influenced. Altered neuromuscular control of the lower limb has been linked with abnormal movement patterns during the above-mentioned tasks, changes in the transverse plane movement at the hip change the loads placed through the lumbopelvic region, knee and ankle (Räisänen *et al.*, 2018a) leading to increased joint stress and microtrauma, which over time can lead to pathology (Casartelli *et al.*, 2015).

It remains unclear if FAI is the consequence of pain and altered hip mechanical movement patterns, or if substandard movement patterns and pain contribute to the advancement of symptomatic FAI (Casartelli *et al.*, 2015). The importance of hip muscle function in relation to movement pattern kinematic and kinetic lower limb normal function has only recently started to be investigated (Powers, 2010; Casartelli *et al.*, 2015). FAI is frequently identified within the sporting adolescent, with continual stress on the physis postulated as an attributable cause to cam development (Wyles *et al.*, 2017). The physical changes encountered during growth and maturation accompanied by the potentially repetitive movement patterns encountered in sport, suggest further investigation and identification of movement patterns and changes in these patterns maybe helpful in profiling those susceptible to FAI.

1.3.2 Knee Complex

Roos *et al.* (2017) followed 108 men's and women's football teams over a 6-year period and discovered that the majority of injuries occurred to the lower limb, whilst they did not identify specific knee injuries, 33.9% of all injuries sustained injuries in women occurred to the knee. In an earlier study (Majewski, Susanne and Klaus, 2006), which reviewed 17,379 athletes over a 10 year period, similar percentages of injury to the knee were reported (40%) with anterior cruciate ligament (ACL) injuries constituting 20.3%, meniscal tears 13.7% and medial collateral ligament (MCL)/ lateral collateral ligament (LCL) 9% of injuries sustained.

Dynamic knee valgus (DKV) is defined as a combination of hip adduction, hip internal rotation and knee abduction and is frequently identified as a lower limb alignment that attributes to ACL and patellofemoral joint (PFJ) injuries (Tamura *et al.*, 2017). Similar to the hip, increases in changes in planes of movement due to increased loads that cause repeated trauma and stress can increase the likelihood of pathology. Like the hip, altered neuromuscular control (NMC) has been linked with poor frontal plane knee control, hip abduction and external rotation strength which are important contributors to valgus control (Hewett *et al.*, 2015; Leppänen, Pasanen, Krosshaug, *et al.*, 2017a; Nae *et al.*, 2017; Barker-Davies *et al.*, 2018). As such, these neuromuscular factors that are thought to attribute to frontal plane control of the knee can be influenced by targeted training programmes.

Numerous studies,(Knaus, 1993; Stickler, Finley and Gulgin, 2015; Comfort, Colclough and Herrington, 2016; Räisänen *et al.*, 2018b) have demonstrated that athletes that underwent neuromuscular training programmes demonstrated improved knee control during vertical drop jump and single-leg squat when assessed with frontal plane projection angles (FPPA). A recent meta-analysis (Donnell-Fink *et al.*, 2015) affirmed that neuromuscular and proprioceptive training programmes that addressed movement pattern deficits, attributed to the reduction in ACL injury by 50% and knee injury by 26.9%. Despite these claims little is truly known on how improved knee control reduces injury risk. It is important therefore to investigate normative movement patterns and changes in those patterns at the knee in both adult and adolescent groups to further understand the role of neuromuscular control in relation to the knee to advance future profiling methods and impact injury risk.

1.3.3 Ankle Complex

As stated by the National Collegiate Athletic Association (NCAA) around 40% of injuries sustained to the foot and ankle complex in collegiate level athletes were classified as ankle sprains (Hunt *et al.*, 2017). Of the other injuries related to the ankle joint – midfoot injury comprised 15%, Achilles 8% and toes 12%, with ankle impingement, contusions and foot and ankle fractures making up the top 2-4 injuries. Of the 1076 students evaluated across the 37 sports, the average time lost from participation was 12.3 days. Interestingly, within this cohort, 28% of injured athletes reported a recurrence of the same injury, and 48% sustained a different lower limb injury but to the same leg. Although the studies primal focus was on the incidence of foot and ankle injuries, the authors suggest that screening for movements that are considered risk factors along with biomechanical evaluation, will assist with an understanding of movement quality on pathology.

Reduction in ankle dorsiflexion and knee valgus have both been allied to acute and chronic injuries such as ankle sprain, instability and impingement across adult and youth populations (Lersch *et al.*, 2012; Mason-Mackay, Whatman and Reid, 2017; Räisänen *et al.*, 2018). Inordinate frontal plane ankle motion as seen with ankle eversion has been associated with Achilles tendon injury (Lersch *et al.*, 2012) and larger knee valgus (Mauntel *et al.*, 2013). Raïsänen *et al.* (2016) found an association in youth athletes between frontal knee plane control and ankle injury, however, they were unable to establish the links between ankle function and valgus at the knee. Unlike Mauntel *et al.* (2013) who linked limited ankle range with increased valgus, Mauntel *et al.*, (2013) also proposed that reduced ankle range attributed to increased hip adduction and subsequent neuromuscular compensation and movement pattern alteration. Whilst these studies provide insight into the role of the ankle on the knee, it remains unclear the role of the knee on the ankle, therefore cause or consequence is still debatable.

These studies (see 1.3.1-1.3.3) have several limitations, screening and the relationship to injury tends to focus around one joint and the corrective patterns encountered at that joint. In relation to the establishment of associated injury risk, the evaluation of the whole compensatory mechanical pattern, rather than one reductionist joint focus, would better inform practitioners around the quality, and individuals' ability to manage the complexity of movement. Thus, generate greater understanding around the relationships of movement patterns and the disorders and injuries sustained to the lower limb, further guiding profiling practise.

1.4 Prediction models and frameworks

Injury examination and risk is a highly intricate issue (Webborn, 2012; Bahr, Clarsen and Ekstrand, 2018) before the preventative approach, models of injury prevention were developed to try to acquis the size and severity of the injury problem, guide implementation of preventative measures which would subsequently change the perceived risk. The addition of feedback loops was later added evaluating the effectiveness of these measures and further guiding healthcare professions with injury prevention implementation (Van Mechelen, Hlobil and Kemper, 1992; Bahr, 2016; Bittencourt *et al.*, 2016). Van Mechelen, Hlobil and Kemper, (1992) formulated a 4-step injury prevention model, which starts with the determination of the extent of the injury (injury burden), the genesis and identification of the mechanism of injury and risk factors (aetiology)- which are subsequently used to inform the addition of a preventative intervention. Cumulating in the final step of evaluating the impact of the preventative intervention on the originally identified extent of the injury or burden.

Whilst van Mechelen, Hlobil and Kemper, (1992) model is generally still regarded as an acceptable model of injury prevention remaining the most prevalently cited within the literature. It is limited in its ability to appraise the psychosocial elements of behaviour, motivation, skill, experience and age of that individual being assessed (Van Tiggelen *et al.*, 2008), as well as their skills, experience and age (Webborn, 2012). The “real-life” context of injury risk factors remains complex, multifactorial and continually organic in their evolution, critics of the model challenge the effectiveness of proposed interventions and preventative strategies that are reliant on monocausal factors that are established as linear mechanisms of injury. To bridge this gap, Finch, (2006) proposed the six-stage translating research into injury prevention practise (TRIPP) framework to address the Van Mechelen, Hlobil and Kemper, (1992) “implementation issue” of establishing injury genesis via singular causative factors. Injury remains a complex issue with intricate interactions of multiple factors around risk and causation, to methodological issues regarding the application of group research to identify the proposed same risks at individual level, and the questionable successful application of adult profiling principles into adolescent profiling systems. The most recent research encourages the consideration of injury as a complex web of determinants, where emerging relationships patterns between risk factors and mechanistic determinants are weighted contextually to adopt a complex systems approach.

1.5 The Rational for Screening

Screening has been widely adopted as part of an identification process of high-risk individuals that drive targeted prevention programmes. Arguably, the most frequently discussed screening tool has been The Functional Movement Screen (FMS) (Wright *et al.*, 2016) which following its emergence into the field of sports science, was quickly adopted into medical and clinical practice. The framework surmises' seven movement-based tasks that are evaluated via measured visual criteria, participants are scored on a 0-3 scale and provided with composite scores. The FMS provided an observable performance of movement patterns that demonstrate if a participant was able to employ the appropriate motor control. Research reports that deficits in neuromuscular ability are associated with elevated injury risk (Moran *et al.*, 2017), neuromuscular control is also considered by clinicians as a modifiable risk factor. Therefore, the use of screening to identify a factor that attributes to injury susceptibility led to practitioner beliefs that screening could identify, prevent or even predict those at risk of injury.

Whilst Cook *et al.* (2014) have strongly advocated that the FMS serves a "directional, not a diagnostic role," screening notably around the FMS method has generated, widespread clinical interest. Preliminary research (Kiesel, Plisky and Voight, 2007; Duncan, Stanley and Wright, 2013) in National Football League (NFL) players proposed that players with a total score of 14 or less had a positive likelihood ratio of increased injury. Subsequently clinicians adopted this cut-off rate, as the score was believed to indicate a greater odd of sustaining an injury. This sparked additional research focus on the use of composite scores from screening tests as injury predictors, further confounding this allegory, that whilst continually un-proven, un-researched and un-founded, screening has a strong predictive value.

There is a duty of care for employers and sporting national governing bodies (NGBs) to assess the health and safety, and health and wellbeing of their employees and sports people (Webborn, 2012; Moran *et al.*, 2017), and interventions that reduce or prevent risk regarding health, well-being and injury in the workplace are now routine and regularly considered an industry standard. The Football Association (The FA), The International Olympic Committee (IoC) and The Rugby Football Union (RFU) all publicised guidelines providing guidance on musculoskeletal assessment to detect and provide a preventative strategy to mitigate risk and procure the health of the athlete (van Dyk *et al.*, 2017). However, the evidence around the efficacy of these practises, involving the direct impact of screening on injury prevention and acquisition rates remain questionable (Moran *et al.*, 2017; Whittaker *et al.*, 2017; Bahr, Clarsen and Ekstrand, 2018).

Whilst the screening rational for injury prediction fails to adequately conclude the diagnostic accuracy of screening tests on injury prediction, conclusions by several authors (Mosler *et al.*, 2017; van Dyk *et al.*, 2017; Bahr, Clarsen and Ekstrand, 2018) still support the use of screening for none-predictive purposes. Whilst rationals for the justification of screening are starting to evolve away for pure injury prediction, there are copious favourable reasons why screening should purposefully remain. Screening is frequently the first point of contact with a new athlete or patient, and thus can provide a broad baseline of present performance and identify current symptoms or issues. It can be the first point of contact to provide education as well as receive information back to the clinician and allow the building of affinity and relationship between the clinician and the athlete, potentially positively impacting the care to the athlete. Finally, screening is simply a mandate within certain settings and the rationale behind its utilisation is the necessary completion of the medicolegal duties of care (Bakken *et al.*, 2016).

Several limitations with terms have also been identified within the literature, with the interchangeability of terminology adding to the confusion regarding the implementation of injury risk mitigation philosophies. It is therefore also recommended that greater effort be placed on the shared language of terms, to reduce confusion and improve future research application. For the purpose of this thesis the following terms will be used with the following definitions, the term profiling will be used in preference to the term screening where the literature allows, due to screenings synonymous associations with a prediction rationale.

Screening

The medical term that is used to identify previously unrecognised diseases by providing the early detection of signs and symptoms, lends itself to the prediction rationale of current concepts.

Monitoring

The collection and collation of information to establish progression, regression or stability over a period of time. Usually quantified or qualified by the use of specific metrics that describe physical qualities of performance.

Profiling

The action of understanding the requirements of the individual and or a sport to inform practitioner decision making regarding programming of rehabilitation or training. Provides a baseline to work from which can be monitored over time for deviations and changes.

1.6 Motion Analysis reliability and validity

Both qualitative and quantitive methods are used in the analysis of human movement. Objective methods such as three-dimensional (3D) motion analysis are widely used within the laboratory and research setting and are regarded as the global gold standard. The quantitive 3D analysis is postulated as reliable (Ford, Myer and Hewett, 2007; Myer, Ford, *et al.*, 2015; Bohn *et al.*, 2016) for measurements of joint angles and joint forces through complex multi-planar tasks (Schurr *et al.*, 2017). Championed to have external validity compared to other movement analysis methods (Bohn *et al.*, 2016), due to complex set-up and sophisticated equipment requirements this technology is not easily applied in the clinical setting, as part of a weekly or even monthly routine.

Most 3D systems use a camera to capture the trajectories of reflective markers attached to body parts during functional movements, frequently these markers do not coincide well to the performance of functional tasks and can frequently involve re-marking of a subject. The further time requirements also increase the difficulty of the practical applicability of the method within the applied setting (Bahr, 2016). Substitute motion analysis options comprise 2D video analysis or via a qualitative visual rating criterion. 2D video analysis is professed to address the limitations of practical field-based applications encountered with the considered gold standard 3D methods. 2D assessment is relatively easy to use – requiring less training and implementation, is readily portable and more cost and time effective (Schurr *et al.*, 2017), it can be used within clinical, training, competitive and indoor or outdoor settings – which arguably makes it a more clinically feasible within the field and for use with large squads or groups.

2D video analysis has been proven to be a valid and reliable alternative to the 3D method, particularly around the quantification of FPPA and knee separation distance. During their study on university students Munro, Herrington and Carolan, (2012) demonstrated high reliability of the FPPA to 3D methods when captured via 2D methods during a drop jump, presenting intraclass correlations values (ICC) of 0.83 – 0.88 in a mixed-gender cohort. Willson and Davis, (2008) examined FPPA in 40 females (20 asymptomatic, 20 symptomatic patellofemoral pain syndrome (PFPS) via 3D analysis and 2D analysis to establish the utility of the FPPA for knee alignment. Although their 2D metrics did not determine joint rotations through the transverse and frontal plane compared to their 3D measurement techniques (accounting for only 23-33% of the variance), the pair determined that FPPA was a reliable method of lower extremity alignment.

There is a growing body of proof that has acknowledged the relationship between comparability of 3D and 2D motion analysis during varied functional tasks such as landing, squatting and running, that demonstrate moderate to strong relationships between 3D motion capture analysis and 2D video analysis of the lower extremity in the sagittal and frontal planes (Munro, Herrington and Carolan, 2012; Gwynne and Curran, 2014; Maykut *et al.*, 2015; Schurr *et al.*, 2017; Dingenen, Staes, *et al.*, 2018; Mostaed, Werner and Barrios, 2018). However, a frequent limitation within these studies has been the absence of trunk and upper limb evaluation in addition to the lower limb. Furthermore, deficits in the trunk (De Blaiser *et al.*, 2018) and upper limb (Williams *et al.*, 2017) have been purported as contributing factors in the loading of the lower extremities, both on take-off and landing, which may impact movement patterns, neuromuscular control and contribute to injury risk in both adult and adolescent populations. The variation and extent of the contribution, especially in adolescents in not widely understood, therefore, further investigation into the reliability of trunk and upper limb motion in addition to lower limb as observed via 2D, and qualitative methods during different functional tasks is important and will be attempted within this study.

Whilst qualitative methods share the advantages of minimal expense, ease of use, practicality (in terms of minimal technology), usability on large numbers and portability as 2D methods, questions around their sensitivity for identifying "high-risk" participants have been posed (Ekegren *et al.*, 2009). Fundamentally qualitative analysis remains subjective to the rater and has been suggested as highly influenced by rater experience, although Harris-Hayes *et al.*, (2014) demonstrated substantial-excellent (κ= 0.75-0.90 intertester reliability between novice and experienced practitioners during a visual rating of the single-leg squat. Work by Padua *et al.*, (2009) demonstrated that the Lower Extremity Scoring System (LESS) was a valid and reliable visual observation tool during jump landings. Whilst the qualitative tools FMS, LESS and Tuck Jump Assessment (TJA) are frequently employed in practice, discussed in research and relatively well known (Padua *et al.*, 2009; Onate *et al.*, 2010), the Qualitative Analysis of Single-leg Loading (QASLS) is less well known.

To date only two studies (Herrington and Munro, 2014; Herrington *et al.*, 2017) have scrutinised QASLS, however, a systematic review by Wilke, Pfeiffer and Froböse, (2017) emphasised its use for preliminary assessment when there was limited clinician time. Unlike the LESS system, the QASLS comprises two functional tests to evaluate the lower limb with consideration given to the upper limb and torso positions during these movements. As previously mentioned the trunk and upper limb position are potential contributors to lower limb load, investigation of their contribution has lacked attention in the previous literature. Due to the inclusion of trunk and lower limb within its composition and therefore the ability to evaluate these potential risk factors, further investigation into the use of QASLS as a profiling tool as warranted.

Quantitive measurements of motion analysis do not undoubtedly assure reliability and validity, and the subjectivity of the qualitative methods of motion analysis does not undoubtedly mean that qualitative methods are less reliable or valid. Both adult and adolescent individuals at the Individuals amateur and elite ends of sport are believed to be negatively impacted by poor movement patterns and neuromuscular control. Movement analysis or "profiling" methods that can be used to identify substandard patterns are important and attractive to clinicians, to place them in better decision-making spaces but also assist with the clinical direction of athlete rehabilitation and conditioning pathways.

Selected methods also need to be valid, reliable, and easily implementable, and both 2D and qualitative measures appear to be useful methods to relevantly collect information around movement patterns in the most practically applicable way. These simpler methods may have the potential to establish the validity and reliability of movement assessment tasks in a sympathetic way to complex systems approaches. Therefore, further investigation and understanding of the potential of qualitative analysis, beyond the singular parameter of dynamic knee valgus, around how the torso and upper limb interacts with the lower limb is warranted.

1.7 Screening Tests Movement Assessment Tasks

To reduce the burden of sports injuries many clinicians look to influence modifiable factors, such as neuromuscular control, weakness and capacity. Many movement control tests have been evaluated within the literature, examples of such include, and are not limited to, drop-jumps, vertical jumps, squats (bilateral & unilateral), lands, lunges and hops (Noyes *et al.*, 2005; Hamilton *et al.*, 2008). Many tests require the use of both limbs at once, rendering comparisons between limbs difficult if not impossible, and are also unbefitting of the pivoting, landing and decelerating sporting movement patterns that frequently occur unilaterally. Unilateral tests make comparisons between sides easier, however, consideration has to be given to the test selection to ensure it actually meets the sufficient physicality of high-performance sporting demand. The most common tests are the single-leg squat, double/single-leg vertical jumps and continual tuck jumps (Fort-Vanmeerhaeghe *et al.*, 2017). Despite these tests being well utilised regularly their reliability in relation to test-retest capability and levels of the inter-rater agreement has not been fully defined.

1.7.1 Single-leg Squat Test (SLS)

Single-Leg Squat test (SLS) is a movement control task favoured by many clinicians within the sporting and clinical sectors. It is selected by practitioners as a means of monitoring leg strength and endurance (DiMattia *et al.*, 2005) because of its clinical utility if space is limited, or as a pre-requisite to jumping and running if an athlete is unable to do so (Barker-Davies *et al.*, 2018). As well as assessing biomechanical variants, such as frontal plane knee control (Munro, Herrington and Carolan, 2012; Raïsänen *et al.*, 2016; Schurr *et al.*, 2017; Räisänen *et al.*, 2018b), it is also used as an outcome measure post-operatively and as part of a return to play guidelines (Herrington, Myer and Horsley, 2013; M. P. Hall *et al.*, 2015). Despite its review within the literature, no standardised method of SLS is described, this makes comparisons between papers difficult. Whilst there may be kinetic agreement (Barker-Davies *et al.*, 2018) the components of movement being compared such as hip angle, knee moments, may not always be the same. Work by Khuu, Foch and Lewis, (2016) has shown differences in movement patterns dependent on where subjects place the none-stance leg, it has not been previously studied if these strategies are normal or part of adaptive patterns. If SLS tasks can demonstrate different movement patterns it is plausible that collection of normative data from different ages and sporting populations would help determine and clarify what observed SLS variants are capable of assessing from both a movement and profiling perspective.

1.7.2 Single-leg Land (SLL)

Whilst drop landings have been extensively researched within the literature (Munro, Herrington and Carolan, 2012; Gwynne and Curran, 2014) and hop tests are well documented (Kockum and Heijne, 2015; Wellsandt, Failla and Snyder-Mackler, 2017), single-leg landings that are not part of a hop battery have received less attention. Generally, unliteral landings are reported as a frequent injury mechanism at the hip (Mather and Ferrell, 2018), knee (Bailey, Selfe and Richards, 2011) and ankle (Hunt *et al.*, 2017). Dingenen *et al.* (2014) demonstrated that those who displayed less hip flexion sagittally required greater frontal plane movements to decelerate their centre of mass upon landing, and SLL task may be more representative as a sporting assessment as it represents different velocities of movement being more physically demanding than an SLS. Only two papers (Munro, Herrington and Carolan, 2012; Gwynne and Curran, 2014) have reported upon the reliability of the FPPA during single-leg landings, due to the proposed increased physical demands during the SLL compared to the SLS, and the acknowledged effect of the position of the trunk, pelvis and upper limb (Schurr *et al.*, 2017) on landing position, it would be pertinent to assess other measurements such as hip adduction, pelvic tilt and trunk flexion during the SLL task.

1.7.3 Tuck Jump Assessment (TJA)

The Tuck Jump Assessment (TJA) was developed as a movement tool to identify flaws in landing during plyometric activities Ford, Myer and Hewett, (2007). Unlike the single-leg loading and landing tasks which only assess landing conditions, the TJA repeatedly allows for the evaluation of jumping ability and landing, reactive strength and ingrained reaction. Which is arguably more reflective of the maximal efforts and maintenance of good quality movement under fatigue required in sport (Fort-Vanmeerhaeghe *et al.*, 2017). Despite the TJA being in use for over a decade (Herrington, Myer and Munro, 2013), there are limited numbers of studies reporting on reliability (Knaus, 1993; Herrington, Myer and Munro, 2013; Fort-Vanmeerhaeghe *et al.*, 2017) with most focusing on university standard participants. Given the potential of the TJA to mimic the greater movement demands of the sport as well as its portability as a practical test, further investigation into its use across different age groups, sporting groups as well as the identification of normative execution was initially proposed. Whilst part of the initial conception of the PhD it was expected the TJA would be analysed as part of the methodology, it was therefore investigated in pilot work and as part of the original data collection. Analysis of the initial data set demonstrated little corroboration between the double leg task and unilateral tasks. As a potentially confounding factor, further analysis of the TJA has been retained for post-doctoral analysis, however as its investigation informed the process of the critique of the profiling literature it remains within the literature review.

1.8 Validity and Reliability

For movement screening to be practically applicable the measurement quantities of the movement task must be identified. For assessment tools to be considered reliable conclusions the same across different assessors and at each application, and for them to be valid each tool must measure what we expect it to measure (Nae *et al.*, 2017; L. B. Mokkink *et al.*, 2018). Additionally, tools should be internally consistent by measuring the same constructs detecting any changes that might occur over a period of time, such as a training block or a competitive season (Nae *et al.*, 2017; L. B. Mokkink *et al.*, 2018).

Batterham and George, (2003) explain reliability as "the quantity of a measure or test that possesses the reproducibility of the same scores repeatedly in the same circumstance." Based on this premise validity is imperative for test reliability. Although reliability does not imply validity, inter-rater and intra-rater reliability is considered an important aspects to further confidence in the validity of any test or tool (Nae *et al.*, 2017). Establishing the reliability of tests, tools and measurements is consequently hugely important, as measures that are contrary from situation to situation inhibit the correct interpretation of research and subsequently impacts on practical applicability.

Validity is described as the accuracy and credibility of a study (Batterham and George, 2003), usually separated into the two components of internal and external. Internal validity implies that measurements are absolutely characteristic of what they measure, and that external validity is the amount and actual applicability of the measurements to other populations settings to the ones selected (George, Batterham and Sullivan, 2003; Nae *et al.*, 2017; L. B. Mokkink *et al.*, 2018). It is paramount to establish that any profiling method or movement quality task used within clinical practises and the research domain is reliable and valid. To assure that meaningful data can be extrapolated from the movement patterns of functional assessment tasks and full application can occur within the practical field, regardless of if they are qualitative or quantitive, must measure the desired parameters and any differences between session and those undertaking the tests as either clinicians or participants.

1.9 Considerations for the adolescent athlete

Several limitations regarding the profiling literature have been introduced, with limited research available regarding whole movement pattern evaluation in adults, research regarding qualitative profiling of movement quality in adolescence remains even more scarce. Numerous athletes from recreational level through to the elite level continue to experience additional and recurrent injuries even following periods of successfully deemed stages of rehabilitation, which frequently results in failed returns to sport and sometimes cessation of sport altogether. This is particularly prevalent within the Under 18's age group where injury related to physical activity is reportedly higher amongst an adolescent age group comparative to adults (Schmikli *et al.*, 2009; Rexen *et al.*, 2016) and is a lead reason why U15s age group drop out of sports altogether (Boström *et al.*, 2016).

There is a growing body of evidence that attributes these high rates of re-injury and initial injury to functional deficits such as neuromuscular control, dynamic and static stability, with all these things penultimatly being underpinned by poor and or insufficient movement quality. Reduced movement quality has been shown to be reduced post-injury in both elite level sport (Hägglund, Waldén and Ekstrand, 2009; Bizzini and Silvers, 2014) at a recreational level across adolescent, adult and older adult age groups (Flanigan *et al.*, 2013). Given the importance of movement quality to a successful return to sport, retaining engagement with sport, and potential identification of predisposed and vulnerable individuals, the proper evaluation of movement quality and the tools by which it is assessed is of great importance. During growth and maturation adolescent athletes potentially face great changes in their centre of mass, NMC and physiological systems, that may be impactful on their sporting performance (Quatman-Yates *et al.*, 2012; Agresta *et al.*, 2017; Cumming *et al.*, 2017; Kozieł and Malina, 2018). Presently, there is a lack of research that has considered the context and impact of maturation on unilateral task performance and movement quality assessment (Emmonds *et al.*, 2020). Children are not miniature adults, and therefore adult findings regarding profiling tools may not be consistent with findings in an adolescent population. Consideration and investigation of this group as a stand-alone cohort is therefore warranted, to further inform and develop future profiling practise which will be more impactful on injury risk understanding.

1.10 Thesis Aims and Objectives

The overall aim of the thesis is to improve MSK profiling by establishing the validity and reliability of a qualitative MSK profiling tool, with the specific aim to deepen understanding of how movement quality changes during growth and maturation within multisport adolescent populations. To meet these aims a number of objectives were devised.

1. To develop valid and reliable methods, and associated measurement error for 2D kinematic and a new qualitative movement assessment tool, during two unilateral limb loading patterns, to embrace the complex systems approach paradigm proposed by injury prevention frameworks
2. To establish what factors, impact the application of 2D and qualitative assessment in the youth adolescent population during unilateral loading tasks, as whilst application of profiling implemented within the adult arena has been inferred appropriate within adolescent populations, this has yet to be fully investigated
3. To establish if performances of the unilateral loading tasks change over a competitive season or training period. This has been postulated within an adult environment, however it remains unclear if longitudinal movement pattern variation occurs within an adolescent cohort
4. To establish the effect of an educational piece on levels of rater agreement and consistency of rater methods, as for profiling tools to be widely accepted within both adult and adolescent populations, there is a requirement for easily administrable methods that are suitably comparable between multiple practitioners and multiple centres.

Chapter Two

2.0 Literature Review

2.1 Chapter Overview

Screening and profiling tests have been routinely used by sports medicine practitioners as a means of evaluating injury risk factors. With the prediction rationale underpinning screening highly questionable (Bahr, 2016; Toivo *et al.*, 2018) and discords between interventions, mitigating outcomes and meaningful application, there is a requirement to scrutinise and re-evaluate the construct of screening and profiling again.

Presently, large amounts of money, time and effort are expended on musculoskeletal (MSK) profiling especially within the adult and youth sporting sectors (Hughes *et al.*, 2018), it is imperative that any MSK screening or profiling strategies produce reliable and valid measures, but are also carefully and thoughtfully applied for the purpose of which they are intended. Across the screening and profiling literature, there is a shortage of critical examination, and many methodological limitations behind the concepts of screening and profiling, that are particularly prevalent within the adult literature and even more pertinent within a youth setting. As with all individuals, participating at any level of organised sport arguably predisposes the individual to some element of training or competition induced injury risk. Unlike their adult peers, young adolescent athletes endure significant physiological, anthropometric and biological changes during maturational and growth processes (Malina *et al.*, 2015). Screening and profiling practices are frequently conducted against this challenging backdrop of intense physical change (Cumming *et al.*, 2017; Rejeb *et al.*, 2017; Hughes *et al.*, 2018; Von Rosen, Kottorp, *et al.*, 2018) that is frequently overlooked by practitioners, and occasionally poorly understood.

Whilst an overhaul of general screening and profiling is more than warranted, the re-evaluation and re-application of profiling is incredibly context specific. The implementation of a profiling tool in one context (for e.g. an adult female basketball team) maybe perfectly adequate, however in another context such as within an adolescent squad it is deemed insufficient.

With this in mind, this chapter aims to provide a critical overview of the literature applicable to MSK profiling, qualitative movement assessment and the appropriate consideration of context around future applications. Using the youth athlete as an exemplar to understand the influence growth and maturation may have on profiling processes to inform future clinical practise. The first section of the review considers the rationale for preventing injury occurrence and the current landscape of injury incidence. The second section explores the relationships behind the rationales for screening and profiling, to identify relationships behind screening rationales for movement quality, injury prevention and proposed identification of risk currently held within the literature.

This leads into the third section which reviews the assessment and monitoring of human movement and associated links to injury. The first purpose defined the outcomes of previously reported research concerning the validity and reliability of kinematic, kinetic and qualitative methods of movement analysis. As there are only a select number of studies that have scrutinised qualitative methods of movement analysis, the emphasis of this section is a narrative review directed towards qualitative assessment tools and movement assessment tasks and the establishment of the validity and reliability of these methods. The final section of the review considers the specific relationships between movement quality and injury risk in the youth athlete. The aim of this was to highlight normative patterns of movement during the movement assessment tasks, to potentially identify the role of context when considering application to the youth athlete through the examination of differences in patterns of movement between youth and adult athletes. For a movement assessment tool to be correctly and effectively applied within this cohort, understanding the impacts or changes that occur during growth and maturation added an important depth to the review to ensure subsequent methodology and analysis maximised clinical utility of the findings.

2.2 The rationale for injury prevention

2.2.1 Why prevent injuries?

Since the early 1970s when William Haddon produced the first conceptual framework for studying injury causes and their subsequent prevention, clinical professions have utilised this matrix to identify modifiable risk factors to target the causal sequence at appropriately deemed points of intervention. Within the context of elite sport, theoretical models for the prevention of sports injuries were formulated from the early 1990s (Saragiotto, Di Pierro and Lopes, 2014). Despite the absence of consensus regarding the efficacy of these constructs on the promotion of good health and improving outcomes of injury and disease, the preventative approach has been a cornerstone of general and sporting medical practise for decades (Bahr, Clarsen and Ekstrand, 2018).

Injuries impact substantially in both the public health and athlete health contexts, the impacts of which can be far-reaching, prolonged and costly. MSK disorders are one of the primary causes of sickness absence in the workplace, which is estimated to currently cost the United Kingdom £20 billion and account for 3-4% of loss of worker time (Squires *et al.*, 2012). Musculoskeletal injuries account for around 20-59% of injuries within the British Armed Forces and are the leading cause of medical discharge (Sharma *et al.*, 2015), not only does this lead to waisted revenue in training costs of individuals but also physical loss of an asset to the armed forces.

Within the context of elite sport, the financial implications, in terms of medical expense and wages lost, of injury are well documented (Bakken *et al.*, 2016; van Dyk *et al.*, 2017). According to a recent editorial review, elite football clubs can expect to incur daily costs of €20,000 for each player absent through injury (Ekstrand, 2016). Financial burdens of injury also cascade into the amateur levels, with amateur rugby league players incurring an average of £110 in direct and indirect economic costs per playing injury (Gabbett, 2001). Acute and chronic musculoskeletal conditions and injury (markedly that of the lower limb) are on the rise within the sporting and non-sporting populations (Squires *et al.*, 2012; Schurr *et al.*, 2017; Whittaker *et al.*, 2017), as such the commerce of injury prevention is ever-expanding as youth and adult amateur and elite athletes, the military and general populations remain susceptible to injury (Rejeb *et al.*, 2017; Soligard *et al.*, 2017; Bahr, Clarsen and Ekstrand, 2018).

Individuals that sustain an injury are not just susceptible to financial loss but will also endure elements of time-loss. Within a general population, this can result in time away from the workplace or study but also from training and playing time (Gabbett, 2001). For the developing youth athlete, this can also manifest as a loss of opportunity for technical and tactical development. During the 2017-2018 season, the RFU reported on an average of 1.8 injuries per match and 60 injuries per premiership team each season and a 37-day recovery time (Rugby Football Union, 2018). As player availability and potential squad rotation becomes less, remaining available players can frequently be required to do more, with a cascading effect on their own injury susceptibility.

Whilst the economic and time-loss burden of injuries are clear. Psychological impacts of the injury, from fear of reinjury through to reduced engagement for mental health benefits, can also add additional barriers and burdens across all ages and levels of sporting participation (Saragiotto, Di Pierro and Lopes, 2014; Von Rosen, Kottorp, *et al.*, 2018). Across public, sporting, adult and youth populations, the most predominant recorded injuries are those within the lower limb. The detrimental effects of individual socioeconomic, health burden costs, and impedance of sporting competitive success, appear to be the primal drivers behind prevention of athlete injury and illness events. Practitioners appear to try to lower the number of injuries sustained to positively impact individual sporting performance and potential team burden. This potentially explains the industry paradigm shift over the last few decades away from retrospective reactive injury management towards that of proactive injury prevention.

2.2.2 Injury occurrence

Injury Incidence

Injury incidence across the whole sporting sector is vast and is fraught with conflicting methodological differences, definitions and proposed future research directions. Within Olympic sports, injury and illness rates appear to be defined by sport at major sporting events (Palmer-Green *et al.*, 2015), national team sports such as rugby, cricket and football appear to be reported seasonally at wither international or national levels (Fuller *et al.*, 2007; Orchard *et al.*, 2016; Fuller, 2018; Rugby Football Union, 2018), and individual sports such as tennis or boxing appear to adopt a missed approach of retrospective and current surveillance of event and seasonal injuries (Loosemore *et al.*, 2015; McCurdie *et al.*, 2017).

Whilst there are data sets on individual sports, there appears to be no national data set on sports injury as a whole, and as such the current total sport-related injury burden on the UK remains unknown. It appears that collective injury incidence data is important to further monitor and mitigate sports injury risk to further inform athlete health and general health services, and medical policies and risk mitigation efforts.

Injury incidence reported in Team GB athletes was 48.2 injuries per 100 athletes or 39% of the 2014 Olympic squad and was much higher than the previously reported 11% at the preceding summer and winter Olympic games (Palmer-Green *et al.*, 2015). Whilst the increased injury incidence may have been attributed to slightly larger data collection periods than previous works, it appears injury incidence between Olympic cycles is on the rise. Increasing trends in injury incidence have also been documented in rugby. Injury surveillance work by Fuller *et al.*, (2007, 2017) during the 2007 and 2015 rugby world cups recorded an average 7% increase in injury incidence from 83.9/1000 player-match-hours to 90.1/100 player-match-hours in 2015. Although there were reductions in injury incidence during player-training-hours (3.5/1000 hours in 2007 to 1.0/1000 hours in 2015), the average days' absent post-injury dramatically increased by 15 days between 2007-2015 (Fuller *et al.*, 2007, 2017). Increases in injury incidence and recurrent injury in English professional football have also been documented in epidemiological studies over the last 16 years, with a reported average of 9.11 injuries/1000 of exposure time (Jones *et al.*, 2019). Other team sports have also documented increases in injury incidence, meta-analysis work has reported injury rates of 53.16 per 10000 hours of cricket match play (Soomro *et al.*, 2018), and 19.1-24.9 per 1000 athlete exposures in basketball (Bird and Markwick, 2016), and 9.08 per 1000 hours exposure in netball (Best, 2017).

The increasing trend in injury occurrence also appears to be occurring in individual sports, with increases of injury incidence over a 6-year period to 148-201 injury incidents per 10000 tennis game exposures during the Australian open (Gescheit *et al.*, 2017), and no difference in injury rates per athlete exposure in either men or women documented over a 4-year period in swimming (Kerr *et al.*, 2015). Within the artistic athlete injury incidence rates of 3.35 per 1000 hours of dance, exposures have been recorded (Lee *et al.*, 2017), and 84.1 per 1000 gymnasts has been recorded at 3 different Olympic games (Edouard *et al.*, 2018).

Despite the issuing of various consensus statements (Fuller *et al.*, 2007; Pluim *et al.*, 2009; Timpka *et al.*, 2014; Bahr *et al.*, 2020; Kliethermes *et al.*, 2020) around the definitions, methodological designs and reporting standards regarding injury incidents, fundamental differences regarding classification and recording of exposure across sporting disciplines exist. Whilst injury and illness epidemiology methodology has clearly advanced, logistical difficulties in being able to collectively define and collate data in such a way different sports can be comparable needs to be addressed. Although 1000 hours of exposure appears to be recommended as the preferred method of injury incidence (Fuller *et al.*, 2007; Bahr *et al.*, 2020), and whilst this might be easier to collect across larger team sports such as football and rugby, exposure measures to this extend might not be as readily available in smaller or individual based sports. Overall sports injury incidence remains a concern and as such, better accessible and standardised methods of quantifying exposure are required before the total injury prevalence problem is fully understood.

Mechanisms of injury

How injuries happen, or the injury cause was identified as a critical step to injury prevention by Van Mechelen, Hlobil and Kemper, (1992). Ten years later the term “injury mechanism” was well established within the sports medicine literature as a biomechanical term to describe the inciting event of injury but its meaning remained ill-defined (Bahr and Krosshaug, 2005). Present-day research does not appear to have advanced definitions further, with a distinct lack of in-depth descriptions into the specifics of injury aetiology. Broadly speaking, if injury mechanisms are described at all, the majority of papers divide injury mechanisms for specific injuries into contact or non-contact or training or competition.

Data providing proposed mechanisms of injury across multiple Olympic sports suggest that contact was implicated in 28% of cases, non-contact in 21% and overuse mechanisms in 19%.

Overall injury incidence was higher during competition (59%) than training (37%), suggesting that the competition events were a greater mechanism of injury that training events (Soligard *et al.*, 2017). During the 2017-2018 senior England men's rugby season similar training incidents were recorded during training (38%) which was lower than the number of injuries sustained during matches. The report (Rugby Football Union, 2018) attributed 52% of match injuries to contact, with an even spread occurring between tackling (28%) and being tackled (24%). Whilst differentiations were made between injury sustained by the tackler or ball carrier it was unclear if the mechanisms behind the figures occurred during match or training time. Training injury mechanism was reported as either non-contact or contact rugby skills, or non-weight or weights conditioning, additional specifics regarding the specific activity e.g. running, pushing, pulling was not included.

A 16-year prospective study in English professional football documented 40% of injuries occurred due to a chronic overuse mechanism, and traumatic injury accounted for 60% of all injuries- although he authors provided no further information on if this occurred specifically during contact or non-contact scenarios (Jones *et al.*, 2019). Whilst injury incidence during tennis competition is widely reported (Sell *et al.*, 2014; Gescheit *et al.*, 2017; McCurdie *et al.*, 2017) the inclusion of specific mechanisms did not appear to be examined by any author.

Although concrete mechanisms of injury across a large sample of sports appears to be sparse, information suggests injury mechanism trends are largely incurred during contact or overuse events, and that training or match specific mechanisms are likely to be sports dependant. Due to the lack of definitiveness within the mechanistic causes of sports injury, it is difficult to fully conclude if profiling strategies should consider procedures that target contact or overuse-based approaches. Given that injury mechanisms occur during training and competition, it is suggested that to identify injury risk, the selection of movement patterns that occurs in both these environments should be investigated. However, the specifics regarding which movements (i.e. squatting, landing, falling, pulling, pushing) might be causal mechanisms which would directly inform the thesis methodology remain unknown.

Seasonal variation

Whilst injury incidence and causes are integral to injury prevention, understanding specific time points during the year or competitive season where injury risk might be greater and prevention strategies more effectual is of clinical interest to practitioners. Seasonal variation and associated fixture congestion has been well documented with peaks in injury rates during pre-season and mid-season winter breaks (Carling, Le Gall and Dupont, 2012; Bengtsson, Ekstrand and Hägglund, 2013; Carling *et al.*, 2015; Jones *et al.*, 2019).

Furthermore, when comparing periods of short-term fixture congestion Jones *et al.*, (2019) suggested that players presented with three matches within a week's period consciously or subconsciously changed their pacing strategies to preserve performance capabilities at a higher demand level. In addition to physiological stressors fixture congestion can also impact cognitive fatigue, inhibiting assimilation of complex information which can increase injury risk. An 11-year follow up study (Bengtsson, Ekstrand and Hägglund, 2013) highlighted increases in muscle injury rates alongside periods of match congestion. The authors demonstrated players, regardless of position, would have an increased risk of injury if repeatedly exposed to fixture congestion and naturally moderated their movement intensity to compensate. This is novel information, as it suggests that regardless of practitioner input, athletes that feel they are susceptible to increased risk of injury will self-regulate their own injury prevention strategies accordingly. Injury peaks have also been identified during the season within rugby league (Fitzpatrick *et al.*, 2018). In their 3-year study, Fitzpatrick *et al.*, (2018) demonstrated increased incidence of injury at the start of the season, and during the month of April when match-time was recorded at its highest. Suggesting seasonal variation during periods of transitions from pre-season to competition, and competition to seasonal breaks. Comparable patterns of mid-winter and summer spikes have been demonstrated in retrospective studies investigating seasonal variation in achilles tendon rupture (Caldwell *et al.*, 2018), and a 5-year study of knee injuries (Moore *et al.*, 2011).

Previous adolescent literature has suggested that youth football athletes may also be subject to injury peaks at particular time points such as during pre-season and after a mid-season break (Lloyd *et al.*, 2020). In additional to seasonal variation, youth and adolescent athletes will also encounter the experience of biological maturation, this process is highly individualistic and its timing, status and tempo will be variable across the same age groups (Cumming *et al.*, 2017). Depending on maturation timing in relation to chronological age individuals can be classified as late, on-time or early maturers (Malina *et al.*, 2015) with the pubertal phase hypothesised as a time of increased injury risk (Swain *et al.*, 2018). Current research regarding the adolescent athlete has been largely dedicated to the cross-sectional evaluation of physiological variables in male football players (Read *et al.*, 2016, 2018), and there are currently gaps in the literature regarding longitudinal assessment of neuromuscular control (NMC).

It remains unclear if seasonal variation within an adolescent population is impacted by growth and maturational related changes in NMC, or if injury peaks are resultant of injury risk factors such as accumulated fatigue and reduced recovery opportunities that can attribute to alterations of NMC (Lloyd *et al.*, 2020). Understanding changes in movement quality variation not just seasonally, but through identification of maturational status throughout a season is of importance to practitioners, to ensure that any performance related changes are due to the application of injury risk modification strategies, and not just resultant of a natural change in the way an adolescent moves. Seasonal fluctuation in NMC appears to be ambiguous within an adolescent population due to an absence of research regarding the repeated capture of in-season NMC profiling. Further research is therefore fore warranted to further understand the interaction between profiling, NMC and biological maturation, prior to its examination regarding influence on adolescent injury risk.

Current research suggests that understanding of seasonal variation of injury prevention is of use to practitioners and coaches to potentially identify if and when athletes may become susceptible to injury. This knowledge appears important as a method of prevention so systems and decisions regarding individual athletes, and full squad cohorts can be adopted accordingly. Ensuring optimisation of recovery periods and preserving of sporting performance.

2.2.3 Summary for the rational of injury prevention

Examination of the current literature suggests that over the last 20 years MSK sports injuries at both the amateur and elite levels are on the rise. Whilst improvements in methodological epidemiological approaches will account for some of the increases in reporting prevalence, it does not account for it all. The rise in injury incidence has been mirrored by a rise in socio-economic costs, that are both impactful on the finances of the individual, elite environment and general health-care providers, and the time of the individuals, wider squad and support staff. In response to the injury burden, practitioners and the research community appear to try to eliminate the initial occurrence of injury, or mitigate its impacts as a minimal standard of care.

In terms of injury epidemiology, there are increasing incidents of sports injuries across a range of individual and team-based sports, but inconsistency around the definition and application of exposure within the research, make the quantification of the injury prevalence problem difficult. Mechanisms of injury appear to be restricted to contact or non-contact-based events, that are classified into the training or competition environment. Whilst this adds breadth to injury mechanism classification, it does not currently provide a depth of information regarding inciting events that may directly inform the selection of screening or profiling tasks or tools that may assist with injury prevention and risk mitigation. Additional research into clinically appropriate profiling tools that capture potential risk factors that occur during training and competition, and in both the contact and non-contact context, would be beneficial.

Finally, the issue of understanding seasonal variation to identify key time points of injury hotspots, to better inform practitioners and coaches around support provision, suggest spikes around start and mid points of a sporting season. The proposed monitoring of meso and macro seasonal variation appears to be applied by practitioners to protect the individual, and others within a squad in team-based settings, to ensure optimisation of periods of recovery and adaptation. Surprisingly, research also suggests that regardless of practitioner input, athletes appear to adopt their own methods of injury prevention, through self-regulation of effort during periods of increased repeated performance requirement.

Overall why the rationales behind injury prevention have been investigated, a lack of clarity regarding the direct links to informed practise regarding screening and profiling remain. Therefore, additional work exploring the rationales of MSK screening and profiling and the links to injury prevention rational is required.

2.3 The rational for screening, profiling and evaluating injury risk

To meet the injury burden problem, and to take an active approach against this burden, practitioners have developed varying models and methods in response to mitigate injury occurrence. Early understanding of injury incidence and the inciting events problem has propagated from a medical model's approach, where the understanding of injury occurrence has been principally directed from a linear biomechanical or biophysiological approach (Hulme and Finch, 2015; Bittencourt *et al.*, 2016). As such, general rationales for injury risk evaluation, screening and profiling have been born out of the underlying principles of prediction, inference and intervention (Jovanovic, 2017), where the common outcome is to reduce or eliminate the MSK injury problem. Therefore, the purpose of this section is to discuss key rationales, current injury prediction models and frameworks and their effectiveness in prevention.

2.3.1 The prediction rational

Identifying and repairing a possible problem before it occurs is a simple coherent human approach (Hulme and Finch, 2015; Hughes *et al.*, 2018). The causal connection of injury prediction to injury prevention by practitioners is highly evident and has been the basis for most screening and profiling methods. Whilst prediction rationales for models have begun to be developed over time (Bittencourt *et al.*, 2016; Bahr, Clarsen and Ekstrand, 2018), inherent limitations to the prediction concepts are the assumed linearity of the injury paradigm. Injury prediction fundamentally functions on the rationale of cause and effect, where input at one point of the process is anticipated to match output at another desired point of the process. However increased changes in one variable do not always result in an equally increased change in the outcome (Bittencourt *et al.*, 2016; Jovanovic, 2017). In initial injury prevention work, predictive modelling worked on the premise that using knowledge of injury causes and mechanisms, certain tools and tasks could be selected to observe and quantify the cause, leading to an establishment of athletes at risk and an appropriate intervention can then be applied (figure 2.1).

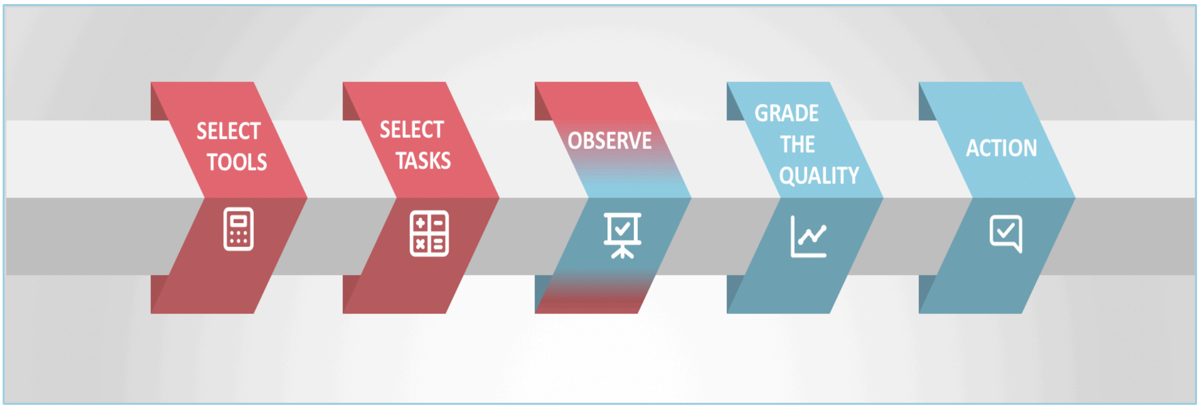


Figure 2.1 A linear process of injury prediction

In 2006, Grey Cook and colleagues (Cook, Burton and Hoogenboom, 2006) presented the first movement frameworks that became the bedrock of participation screening to analyse fundamental human movements. Whilst the authors have strongly advocated it is a directional not a diagnostic model, the cited main goal of the functional movement screen was to determine those “who possess or lack, the ability to perform certain essential sporting movements – to decrease injury and enhance performance” (Cook, Burton and Hoogenboom, 2006).

Several authors subsequently sought to identify the use of the movement screen and relationships to injury risk. Kiesel, Plisky and Voight, (2007) investigated the fundamental movements of the screen in American football players exploring the relationship between player scores and serious injury. Results demonstrated that athletes with a movement screen cut off score of <14 had a greater chance to sustain an injury over the course of the competitive season. The relationship between a screening or profiling score and injury risk appeared to have been established, further cementing the predictive rationale for injury prevention, that was quickly adopted into medical and clinical practice.

The further development of movement screening tools became a crucial component in modifying and predicting injury risk, with risk profiling and screening tests generating widespread clinical interest. Several prospective cohort studies emerged establishing normative data sets of movement screening in college students (Bardenett *et al.*, 2015), male and female multi-sport athletes (Warren, Smith and Chimera, 2015), and military personnel (Teyhen *et al.*, 2012; Kazman *et al.*, 2014). Cut-off values were largely varied across populations (ranging from 13.1-16.9) and data-sets around the diagnostic accuracy and predictive ability of screening and profiling tools was inconsistent and contradictory.

Amalgamation of the predictive literature regarding movement screens has been completed in three recent systematic reviews (Dorrel *et al.*, 2015; Bonazza *et al.*, 2017; Moran *et al.*, 2017) which all provided contradictory conclusions concerning predictive value. Bonazza *et al.*, (2017), conducted a systematic review and meta-analysis on 25 studies in total with nine focusing on predictive value. Results concluded that rater-reliability of the tool was excellent and sores <14 had predictive value. Although there were large numbers of papers reviewed the authors did not mitigate for injury prevention definitions and clustered all papers together. This is in contrast to reviews by both Moran *et al.*, (2017) and Dorrel *et al.*, (2015), who unlike Bonazza *et al.*, (2017), used the addition of diagnostic frameworks to better clarify injury definition and the methodological quality of their chosen papers. Both authors concluded that the use of movement screens as diagnostic frameworks was low to insufficient as a predictive tool.

In more recent times the "predictability" rational for screening and profiling has become more questionable and is further discussed in section 2.3.4. Sports injury is a hugely complex problem, and the prediction of complex problems is difficult, multi-faceted and hard (Hulme and Finch, 2015; Bittencourt *et al.*, 2016; Jovanovic, 2017). AS such, the most recent injury models and frameworks have moved towards a more integrated approach to understand the complexity of the relationships between causes of injury in a more holistic, conjoined process. This has greater accommodation of a non-linear nature of sports injuries that can be better capture and address a complex systems approach.

Predisposition and susceptibility

As the prediction rationale for injury prevention has evolved so has practitioner understanding regarding athlete predisposition and susceptibility to injury. Early models of sports injury prevention viewed athlete predisposition to injury in the same way as the prediction rational. In the early 1990s, injury susceptibility was reduced to singular biomechanical or behavioural parameters that worked along a linear process with a start and an endpoint. With predisposition described via multiple isolated individual factors that followed a uni-directional chain of causality (Leveson, 2001; Hulme and Finch, 2015).

Predisposition and susceptibility were a static and rigid process, with risk factor identification occurring at the individual component cause level where predisposition was characterised by intrinsic factors and susceptibility were determined by the interactions with external risk factors alone (Meeuwisse, 1994). Whilst early research added to the knowledge base of inciting events and singular parameters, it did not reflect the dynamic nature of the sporting environment where odds around injury risk are changing all the time.

Subsequently, additional frameworks (Finch, 2006; Meeuwisse *et al.*, 2007; Bittencourt *et al.*, 2016) have helped shape practitioner understanding of predisposition and susceptibility, by developing the conventional injury prediction perspective away from a linear paradigm to that of more dynamic modelling. In more recent times, the rationale for screening and profiling has begun to shift towards that of the complex systems approach. Susceptibility to injury within this context is an organically, ever-evolving process that is continually responding to the adaptational changes of the sporting environment (Hulme and Finch, 2015). Not only does the risk factors themselves change depending on the sporting paradigm, but so does an athlete's predisposition to those risk factors. Adopting a complex systems approach allows for the exploration of relationships between a multitude of risk factors across multiple contexts, which in turn improves the identification of preventative strategies and more targeted interventions for mitigation of identified risk (Quatman-Yates *et al.*, 2012; Bittencourt *et al.*, 2016).

It appears from the above literature that injury occurrence and predisposition are complex, evolving and multi-causal, and as such, the future selection or design of MSK profiling tools has to be homeostatic (continually adjusting to conditions that are best) and agile enough to keep up with the rate of change of the individual, but also the rate of change of the context or environment they interact in.

This is an important finding for the methodological considerations of this thesis. To further advance and understand the injury prevention process, a selected system of profiling has to be able to holistically analyse variation and provide scrutiny of interactions within that variation. Moving a practitioner into a better decision-making space to provide real-world responsiveness to the injury burden problem.

2.3.2 Injury prevention models and frameworks

Injury examination and risk is a highly intricate issue (Webborn, 2012; Bahr, Clarsen and Ekstrand, 2018) prior to the preventative approach, clinicians and researchers have aimed to capture the risk of injury by acquiescing the size and severity of the injury problem – and to reduce these risks by aiming to understand causes and mechanisms of injury to guide introduction of preventative measures. Models of injury prevention have been developed to try to understand risk, guide the implementation of the preventative measures, to subsequently change the perceived risk and effectiveness of these measures providing feedback loops to guide coaches and healthcare professionals with injury prevention implementation. The complexity of which adds further burden to practitioners comprehension regarding the limitations and efficacy of profiling, and screening (Hughes *et al.*, 2018).

To better understand current applications of the injury prevention research to further inform the methodological approach required for a prospective study on MSK profiling concerning injury risk. A sequential evaluation of the previously mentioned key injury prevention models was included below (figure 2.2).

The majority of injury prevention and injury prediction frameworks are underpinned by the epidemiological triad of injury prevention pioneered through the Haddon Matrix (Haddon Jr, 1974). Dividing injury into three distinct phases (pre-event, event and post-event), the Haddon Matrix has been extensively used to conceptualise frameworks regarding injury prevention and prediction across multiple sporting contexts.

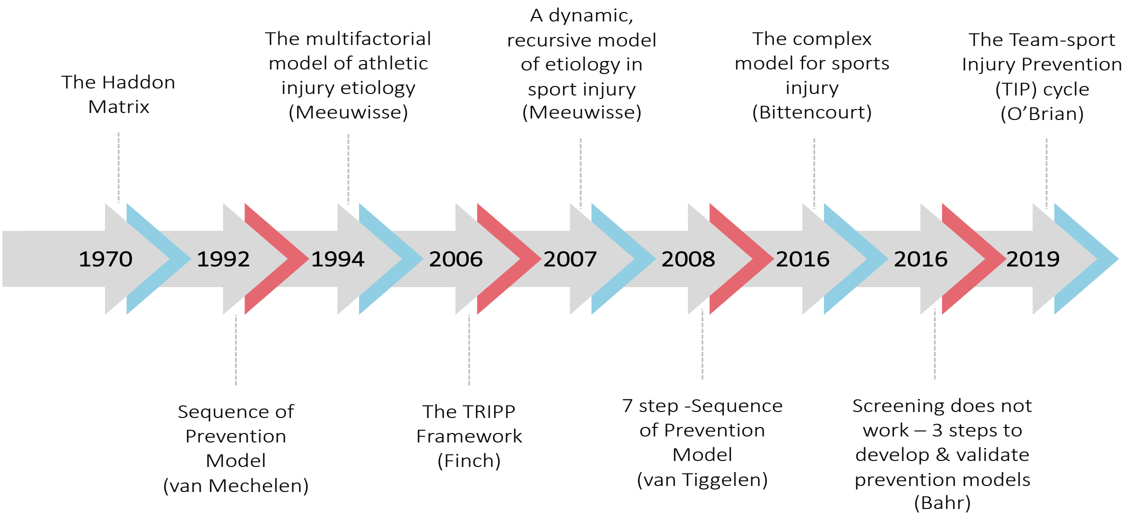


Figure 2.2 Sequential timeline of prevalent injury frameworks

One of the first theoretical sequences of injury prevention was outlined by Van Mechelen, Hlobil and Kemper, (1992). The sequence of prevention compiled 4 key steps (figure 2.3) which starts with the determination of the extent of the injury (injury burden), the genesis and identification of the mechanism of injury and risk factors (aetiology), (where subsequently both injury burden and aetiology are used to inform the addition of a preventative intervention), before cumulating in the final step of the evaluation of the influence/impact of the preventative intervention on the originally identified extent of the injury or burden. Almost simultaneously, Meeuwisse, (1994) proposed a similar pathway of cause where athletes became vulnerable to injury due to interrelations between extrinsic and intrinsic risk factors (Roe et al, 2017). Whilst both these models sought to identify and address factors of injury onset and appropriate risk management, through advancement of causation and the relationship to a multifactorial approach. Both models adopt a simplistic identification of isolated parameters in a singular linear relationship to cause. The inability of the reductionist approach to recognise multiple factors at multiple levels of influence, only allows a practitioner insight into a segment of the total injury prevention picture (Bittencourt *et al.*, 2016).

Whilst van Mechelen, Hlobil, and Kemper (1992) model is generally regarded as an acceptable model of injury prevention, it is limited in its ability to appraise the psychosocial elements of behaviour, demeanour, and motivation of that individual being assessed (Van Tiggelen *et al.*, 2008), as well as their skills, experience and age (Webborn, 2012), and has therefore been challenged around whether proposed interventions and preventative strategies can be fully effective and implemented within the "real-life" context. To bridge this gap of transforming research into practise, Finch (2006) proposed the six-stage translating research into injury prevention practise (TRIPP) framework (figure 2.4) to address the “implementation issue” of the van Mechelen, Hlobil, and Kemper (1992) model as well as highlighting the efficacy of the research around the robust testing of the preventative strategies in relation to study design and reporting rationales for selection.

Concurrently, (Meeuwisse *et al.*, 2007) also moved towards the inclusion of the influence of context, revising the model to include dynamic recursive evaluation (figure 2.5) of athlete behaviours and repeated exposure to understand the changing contexts into which any intervention was applied (Roe et al., 2017). Whilst both frameworks advanced the previous linear and static etiological models to a more dynamic approach. The Tripp and dynamic recursive models did not fully address the dynamism of injury interventions. The absence of interpersonal and systematic components doesn’t fully recognise the non-linearity of sports injury biological processes (Hulme and Finch, 2015; Roe *et al.*, 2017), and as such negated the concept that several risk factors will have several complex interactions.

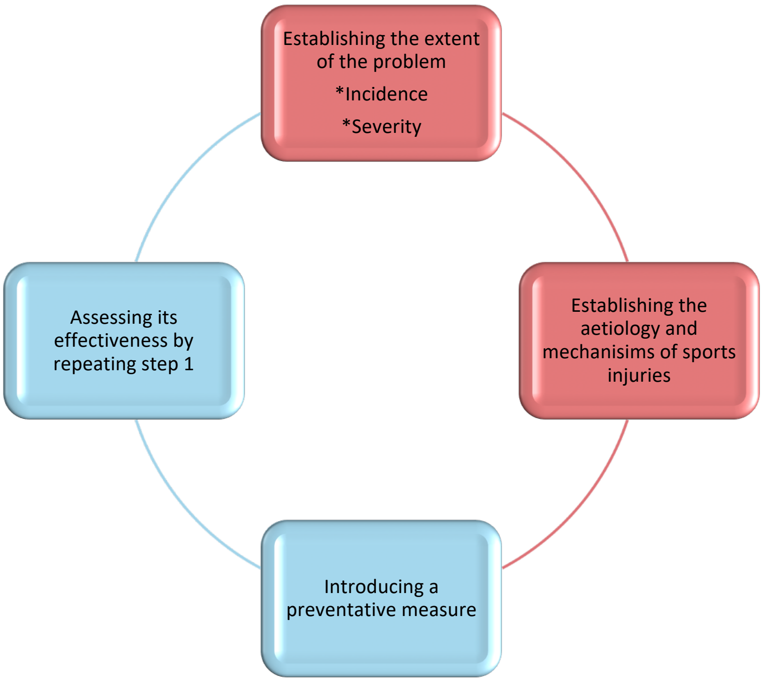


Figure 2.3 Sequence of injury prevention (Van Mechelen et al., 1992)

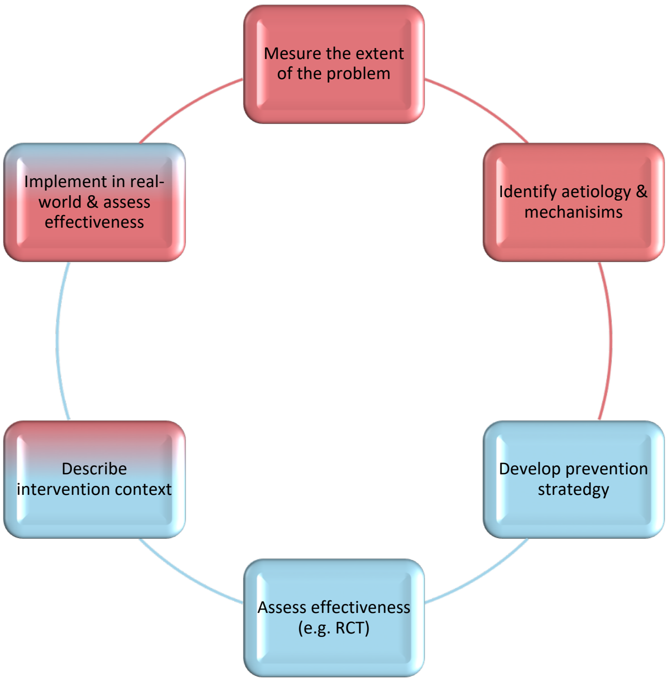


Figure 2.4 Translating research into injury prevention practise (TRIPP) framework (Finch, 2006).

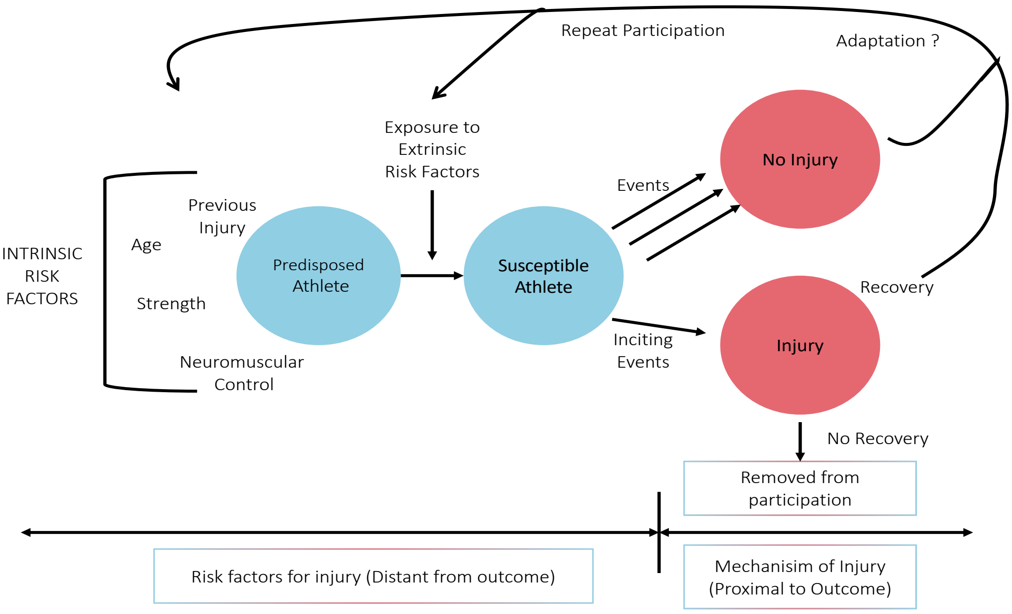


Figure 2.5 Dynamic, recursive model of sports injury (Meeuwisse, 2007)

Almost a decade later, Bittencourt *et al.*, (2016) revisited the dynamic models and further expanded on the multifactorial approach by utilising a "web of determinants" (Figure 6.2), By acknowledging the non-linear injury occurrence and incidence process, but highlighting that the same factors and mechanism will have different outcomes for different athletes she was further able to integrate the athlete and environmental context within the overall system context. With consideration given to the weights and interactions of how the risk factors interact individually, environmentally and contextually, the complex systems approach model (Bittencourt *et al.*, 2016) demonstrated the spectrum of athlete response across the continually ever-evolving interactions throughout the entire sports injury risk system.

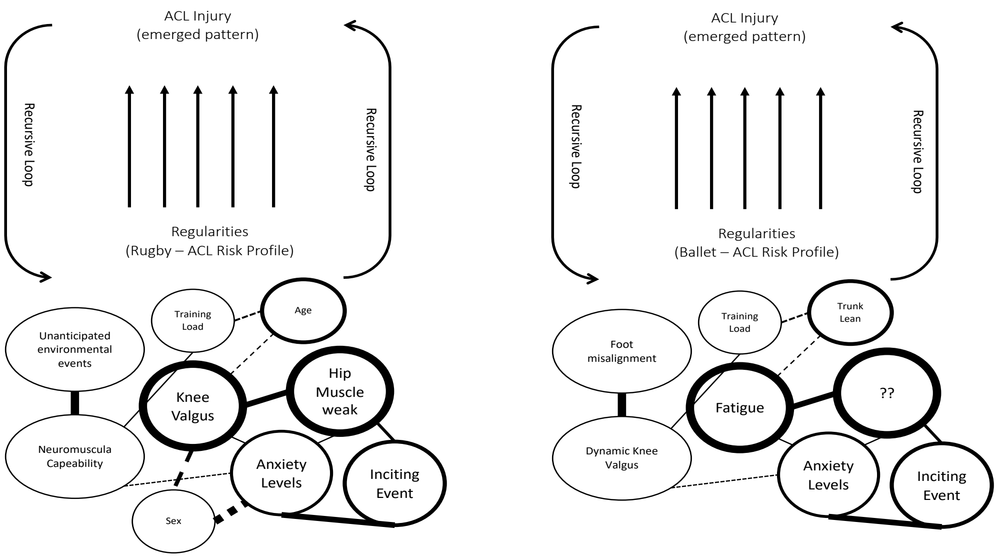


Figure 2.6 Web of determinants approach (Bittencourt, 2016)

In a recent opinion piece, Bahr, (2016) challenged the premise around injury prediction, calling for the invalidation of screening and profiling frameworks altogether. Due to the continuing nature of profiling data, the group have argued that categorisation of test-score cut offs and subsequent determining of high or low risk athletes difficult. As such the predictive approach of identifying a problem and resolving that problem before it happens is troublesome (Bahr, 2016). Whilst the opinion piece highlighted the flaws in many practitioners' rationales for selection of profiling, and potentially exposed the sports science field requiring a better understanding of the tests and tools they are selecting. It is proposed that the three-step validation approach suggested by Bahr, (2016) further demonstrates the reductionist intervention approach rather than the complex context solutions advance.

Although the opinion paper has positively encouraged the re-evaluation around the narrative of injury prediction models and frameworks. It has failed to acknowledge the non-linear biological processes of dynamic nature of injury risk. The three-step process of establishing the relationship between a marker and injury risk, the validation of profiling properties and re-evaluation of the intervention further promotes the singular solution dichotomous approach of perfect classification into those who will or won't sustain an injury. Whilst profiling tests may not provide a definitive outcome, they do still provide predictive value (McCunn and Meyer, 2016; Hughes *et al.*, 2018). Profiling and screening results allow a practitioner to place a value on a physical quality, which can provide a direction of travel for decision making around injury risk and subsequent decision to provide intervention or not.

Most recently, researchers (O'Brien *et al.*, 2019) have begun to acknowledge the limitations of syntax proposed by Bahr, (2016), but to consider and build on the complex systems approach advocated by Bittencourt *et al.*, (2016). The most recent injury model presented in the sequence is the team-sport injury prevention (TIP) cycle (figure 2.7), has adopted the approach by considering injury prevention a continual recursive process, that requires continual evaluation of the context and advances the application of learning from previously on in the process (O'Brien *et al.*, 2019).

Over the last twenty years it appears the sequence of prevention models have evolved from a singular one-dimensional solutions approach to that of a multi-factorial, multi-level interactive approach. It is clear that injury prevention and injury risk mitigation remains highly challenging and still has a long way to go, but after consideration of the historical context, for the advancement of any future prospective studies a mixed methodological design that is complimentary to the complex systems and epidemiological approach is the required direction.

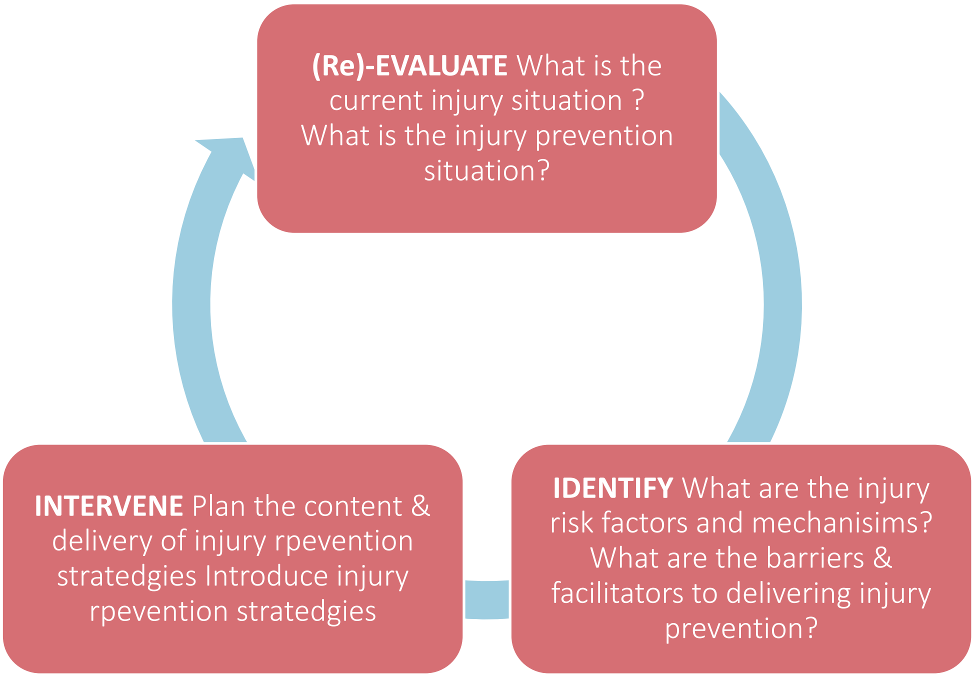


Figure 2.7 The Team-sport injury prevention cycle (TIP) taken from O'Brien et al, (2019)

2.3.3 The effectiveness of injury prevention strategies

Regardless of the framework approach to injury prevention, a key feature of most models in the introduction and evaluation of measures to reduce the impact or mitigate the risk of injury. Despite the increase in research papers containing targeted intervention strategies, the efficacy of these strategies is mixed. The purpose of this section is to provide a brief analysis of the effectiveness of current injury prevention strategies and their relationships to the rationales for screening and profiling of injury risk.

Risk Factors

Risk factors are generally described as the pathways to injury within current models and frameworks are subdivided into internal and external risk factors, and inciting events (Windt and Gabbett, 2017). Some of these factors are non-modifiable whilst others are modifiable (Meeuwisse *et al.*, 2007), and as such modifiable risk factors comprise the majority of the research focus. The main risk factors targeted by practitioners are strength (Bell *et al.*, 2013), equipment (Vriend *et al.*, 2017), exposure to load (Gabbett and Whiteley, 2017) and neuromuscular control (MNC) programmes (Ekegren *et al.*, 2009; Lockhart and Stergiou, 2013; Barden *et al.*, 2020).

From a biomedical prospective, at a tissue damage and prognosis level, an injury is the same injury regardless. When considered from a contextual stand point, patellofemoral pain will present different problems and require different solutions in a ballet dancer comparative to a basketball player (Bolling *et al.*, 2018). As such without context the identification of risk factors alone is not enough to identify athletes at risk.

Should interventions be applied by the independent risk factor or independent pathology?

There have been numerous systematic reviews (Vriend *et al.*, 2017; Bolling *et al.*, 2018; Barden *et al.*, 2020) and prospective studies (Hewett and Myer, 2011) that have evaluated injury prevention strategies, with strategies usually categorised by interactions that target a particular pathology (i.e. ACL, lateral ankle sprain), or target a particular isolated muscle group or movement (such as DKV, gluteal weakness).

According to a recent systematic review by Vriend *et al.*, (2017) into injury prevention interventions the majority of the sports science literature evaluates interventions on injuries to the lower limb, predominantly that of the knee and ankle, and that the majority of research was conducted within football (28%) or rugby (13.8%). However, the focus of the review was on acute sports injuries not overuse based injuries. Whilst acute injuries do occur, overuse injuries are more common in the spine (Kim *et al.*, 2019), and upper limb (Allen *et al.*, 2019), and therefore the exclusion of overuse injuries may have biased available preventative studies to that of the lower limb. Despite this there appears to be a general paucity of research regarding efficacy of injury prevention intervention into that of the upper limb.

Injury prevention programmes of the lower limb generally look to target the knee – notably ACL injuries or the DKV movement specifically (Myer, Bates, *et al.*, 2015; Hewett *et al.*, 2016; Mette K. Zebis *et al.*, 2016). Programme content includes strengthening, stretching, balance exercise with the emphasis on NMC and proprioceptive training thought to reduce joint moments and landing forces associated with the neuromuscular and biomechanical risk factors of ACL injury (Donnell-Fink *et al.*, 2015; Zebis *et al.*, 2016).

In their randomised controlled trial (RCT) of volleyball and football athletes Zebis *et al.*, (2016) reported that a 12-week injury prevention programme altered a neuromuscular pattern during a cutting manoeuvre that is associated with non-contact ACL injury. Whilst the authors documented EMG changes in hamstring to quadriceps muscle pre-activity prior to foot strike, which they argued induced a greater hamstring based protective motor strategy. The reported injuries during the intervention period in the control group were just classified by joint location (4 ankle, 3 knee), the impact of the injury prevention programme specifically on ACL injuries was not recorded. The authors also did not find any specific impact of the programme on biomechanical risk factors. This is in contrast to previous research (Myer, Ford and Hewett, 2005) who demonstrated NMC induced benefits on biomechanical factors of ACL injury risk. This difference in conclusion between the two papers could be attributed to task selection, Myer, Ford and Hewett, (2005) participants were considered from a frontal plane and Zebis *et al.*, (2016) cutting task involved evaluation of the transverse/sagittal. Whilst neither author commented on the movement plane of the task, it does further highlight the importance of context when evaluating and applying prevention programmes and the limitations of application if multiple parameters are viewed in a singular way.

Interestingly, in a meta-analysis by Donnell-Fink *et al.*, (2015) which included 24 studies evaluating prevention of general knee injury prevention, no significant association was discovered between any single training component and prevention of knee injuries generally or ACL injuries specifically. Overall NMC based prevention programmes were better at preventing knee injuries if started in the pre-season (IRR 0.237) comparative to in-season (IRR0.754), and whilst interventions has a protective effect they were statistically none significant. Short and Tuttle, (2020) also found a protective effect for decreasing injury risk in load management pathways started at pre-season over those started in-season. This is interesting information which suggests that the efficacy of injury prevention strategies is not only reliant on the context of the intervention but the timing as well. As such any future frameworks, models or interventions may benefit from multiple phases of evaluation over a training or competitive season or period.

According to Leppänen *et al.*, (2014) studies on injury prevention strategy concerning training programmes increased three-fold within a seven-year period, and as such Doherty *et al.*, (2017) reported there was such a large number of systematic reviews concerning ankle sprain interventions alone (n=<6,000) that considering individual papers was becoming impossible for practitioners. Subsequently multiple papers have addressed injury prevention programmes via injury prevention types or specific injury prevention methods. Authors (Leppänen *et al.*, 2014) have expressed concern that it is now improbable that practitioners can identify the specific aspects of an injury prevention strategy is influential on injury risk factors and which aspects are ineffective components. If the above review is considered within the context of the injury prevention models and frameworks discussed in section 2.3.2, it is likely that the opinion expressed was reflective of the earlier singular outcomes.

If the same concern is viewed within the context of the injury prevention complexity models (Bittencourt *et al.*, 2016), it is likely that the efficacy of injury prevention strategies will come not from any isolated single strategy, but in the interactions of the different strategies of injury prevention. The majority of studies that evaluate injury prevention strategies appear not to have fully made the shift to a complex systems approach that can address multiple associated strategies of prevention. This information demonstrated a misalignment between current injury prevention models and frameworks and injury prevention efficacy studies, as such it remains difficult to assess the effects of injury prevention interventions as an entirety.

Six systematic reviews on injury prevention studies in ankle sprains (Doherty *et al.*, 2017), rugby (Barden *et al.*, 2020), general sports injuries (Leppänen *et al.*, 2014), sports specific or general approaches (Mugele *et al.*, 2018), ACL and knee injuries (Donnell-Fink *et al.*, 2015) predominantly demonstrated that researchers have focused on developing interventions rather than understanding of the contexts to ensure successful implementation of prevention strategies. Each author identified this as the key action of future research, prior to even being able to successfully begin to identify successful and non-successful injury prevention strategies.

In 2014, Leppänen *et al.*, completed a systematic review and meta-analysis of randomised controlled trials that examined the effects of any preventative intervention on any aspect of sports injury. Analysis included sixty studies that included insoles, bracing and thirty-six of which analysed training programmes. Studies were limited to level I evidence and were classified into six highly generalised physiotherapeutic areas that classified training into balance-board, warm-up, strength, guided running and multi-interventional. When classified via odds ratios (OR 0.55, 95%CI 0.46-0.66) training programmes were demonstrated as effective in reducing injury risk, however injury prevention videos demonstrated no predictive effect. Whilst the authors advocated further RCTs with wider-scale application to better improve preventative actions, this is in contrast to the later findings (Barden *et al.*, 2020).

The systematic review by Barden *et al.*, (2020) included 74 studies that evaluated implementation not efficacy of injury prevention strategies across rugby league and union. The majority of papers considered preventative equipment, with only 7 reported to have considered NMC based training programmes. Most studies failed to identify links between a preventative intervention and a performance outcome. Whilst Barden *et al.*, (2020) also proposed a greater need for focus on wider-implementation of preventative strategies. They argued that due to the overly controlled nature of RCT the complexities of injury prevention strategies cannot be appropriately addressed. To encourage the wider uptake and implementation of injury prevention, research is required to move away from RCTs to more pragmatic mixed method or qualitative designs, that are better placed to expedite the process of translating research into practise. Thus, addressing the real-world implications of prevention strategies and better placing practitioners to address intervention efficacy.

Methodological constraints have also been described as the main limiting factor in exercise related interventions in the prevention of ankle sprains and chronic ankle instability (CAI) (Doherty *et al.*, 2017). Results analysing the impact of primary and secondary outcomes following ankle sprain and CAI suggested unanimously that exercise therapy improved self-reported function in both injuries and injury incidence. Whilst the authors linked risk factors to performance outcomes, they did not provide information on how injury incidence was reported in any paper examined. The lack of information regarding injury rate and injury risk expression, limits comparison to other reviews, but further demonstrates the inadequate reporting of specific information regarding prescription, exercise selection and longitudinal application, which is a common limitation in the intervention studies literature. Despite the disparities none of the 46 papers reported on implementation which could explain the absence of evidence connecting intervention impact to primary and secondary outcomes. The study concluded that evidence for preventative exercise interventions were strong.

However, further work examining general versus sports-specific injury prevention programmes concluded there was no consensus regarding best exercises or batteries of exercises for specific or general injury prevention (Mugele *et al.*, 2018). Twenty-eight articles were included in the final evaluation, that suggested injury prevention programmes range from singular exercises to whole programmes. Programmes tended to focus on one or two emphasis (e.g. plyometrics, strength), were performed 1-6 x week for 5-90 minutes over 4 weeks to 4 years. Both sports-specific and general injury prevention programmes graded injury prevention efficacy on a reduction of overall injury rates, not an impact on injury outcomes. Whilst the authors concluded that injury prevention programmes contributed to injury risk reduction, they could not quantify by how much or how long for. They further proposed future research focus on different age groups and sporting disciplines to allow researchers to draw more specific conclusions.

There appears to be some evidence within the generalised systematic review approach that exercise interventions and programming influences strength, proprioception and performance, although the information around specifics of exercise dosing as an intervention is poor. As such full understanding of links between the injury prevention frameworks and models and the efficacy of the interventions themselves, remain elusive.

The role of movement quality

Within sports science the majority of injury prevention strategies appear to be underpinned by modifiable elements of human movement, with short and long-term differences in biomechanical measures greatly associated with changes in injury risk (Dingenen, Blandford, *et al.*, 2018).

There are multiple factors that influence movement, but poor outcomes of movement or poor movement quality have longstanding been associated with injury risk and increased injury predisposition (Myer, Ford and Hewett, 2005). Therefore efforts to capture and assess movement quality whether from a general proficiency, strength, balance, range or coordination perspective are the most common injury prevention strategies (Rey *et al.*, 2018). The most frequently documented movement quality preventative strategies relate to the knee, particularly the ACL pathology and that of DKV (Short and Tuttle, 2020).

Bonato, Benis and La Torre, (2018) examined the effects of a neuromuscular control programme on changes in CMJ and Y-balance test scores in 160 elite female basketball players. The study revealed significant differences in strength and postural control measures between the intervention and control group, with significant between group differences in injury incidence and rate. Despite the effects of NMC programme the authors used a great many factors that would have addressed multiple risk factors and it remains unclear if specific exercises may have elicited the noted changes.

Similar limitations were also identified in two systematic reviews (O'Brien and Finch, 2014; Whittaker *et al.*, 2017) that aimed to determine the association of the role of poor movement quality in relation to lower extremity sporting injuries. Both authors reported low-level evidence that was limited by lack of information regarding the specifics of content and implementation, with both papers recommending future research focuses on specific movement quality outcomes followed by accuracy of diagnostics and implementation of strategies. Davies, Myer and Read, (2020) demonstrated that the use of hop tests as performance measures post ACLR demonstrated excellent reliability, specifically in terms of time or distance travelled outcomes. Whilst performance outcomes alone were considered clinically acceptable, quantification of performance alone is not enough to provide a practitioner with a complete picture of an athlete's status. The authors suggested consideration of "how" a task is executed is an important aspect of NMC that should be further examined. This suggests that movement quality is an import but complex aspect to injury prevention and return to play protocols, however movement quality and performance outcomes may not change at the same pace in the same way. Interestingly the majority of movement quality research is assessed by quantitive means which does not necessarily lend itself well to a contextual methodological process. Quantitative measurements find generalisable unique truths that fit with previous reductionist injury frameworks, qualitative methods are capable of recognizing multiple realities and interpreting relationships via a more organic approach (Bolling *et al.*, 2018), which maybe better applied to complex system approaches.

Overall, research appears inconsistent regarding movement quality as a risk factor, whilst its role in assessment appears to be a gateway to injury risk reduction, the literature appears to support the continual use of movement-based injury prevention strategies. Greater clarification and methodological rigour are required around the context of the intervention and its implementation, if the most relevant movement quality outcomes and interventions are to be successfully applied.

.2.3.4 Summary of the rational for screening, profiling and evaluating injury risk

It appears that there is a gap in the literature in terms of injury risk reduction and practical application which currently hinders wider understanding of efficacy of injury prevention strategies. There also appears to be gaps between evidence, clinical practise and real-world implication due to poor implementation and understanding of the context of an intervention (Barden *et al.*, 2020), which is further impacted by interchangeable terminologies. The review of the injury preventions models and frameworks, and efficacy of injury prevention strategies had highlighted that sports injuries are comprised of numerous interrelated factors that are continually fluctuating and changing. There appears to be voids between the latest complexity frameworks and interventional strategies. Whilst frameworks and models of injury prediction and prevention acknowledge the complexity of the human movement system, and its many moving parts along an ever-changing continuum of time. The strategies and interventions currently applied within the injury prevention research still appear to reflect approaches of older isolationist frameworks. Singular solutions are still researched and frequently limited to a specific point in time, which makes the evaluation of injury prevention strategies difficult and ineffective.

It is clear that movement patterns and the context of such are resultant of many interactive components, and that whilst the identification of risk factors are an important aspect of injury mitigation, no studies have clearly defined links to identification of risk factors to those individuals at specific risk. The latest injury prevention models and frameworks advocate that to better understand the how and why of injury, context and complexity needs to be addressed and that evaluation of future interventions also need to move beyond isolated approaches by addressing the contexts of how and why interventions are successful. NMC and movement control remain the most adopted intervention in sports science research due to time efficiency and clinical utility, and have a clear on-going role to play in injury reduction.

Current evidence is lacking in its ability to keep up with the natural rate of change and variability observed with human movement, and as such future prospective work that wishes to address injury reduction assessments and interventions need to consider complex approaches, with plentiful feedback loops of evaluation over multiple time frames. There is a lack of available data linking injury risk factors, complex systems approach and interventional outcomes. Movement quality can be assessed using a range of quantitive and qualitative methodologies, with limitations present in both models that are potentially attributable to the selected study designs. The subjective nature of qualitative methods has been questioned regarding its suitability for profiling methods. Consequently, authors will defer to quantitative study designs that provide more perceived objective parameters. Whilst these study designs potentially provide more effectual results, the omittance of subjectively and complexity which is inherent within movement inhibits there application into real word scenarios (Barden *et al.*, 2020). Resulting in poor external validity or studies that are solely designed with internal validity in mind. To improve this process, study designs that pragmatically consider a qualitative or hybrid design that adopt a mixed methods approach could greatly improve profiling measures. It is therefore suggested that future profiling and screening systems need to have targets as a component of the profiling system not as focused definitive solutions, to allow for continued adaptability to a range of individuals and a range of performance contexts.

2.4 Assessment and monitoring of human movement and links to injury

The previous sections of this review have highlighted current rationales for preventing injuries, along with exploration of the evolution of injury prevention models and frameworks and effectiveness of current injury prevention strategies. Whilst an understanding of current rationales, limitations and knowledge gaps is important, and movement quality appears to be the most easily modifiable clinical strategy to address risk factors. To advance the development of future profiling tools for practitioners, understanding the current assessment and monitoring tools of human movement and potential links to identify injury risk is important. This section therefore will provide a narrative discussion of currently identified movement quality risk factors and proposed links to injury, movement analysis methods, movement assessment tools and tasks and the validity and reliability that underpin the current concepts.

2.4.1 Movement Quality and links to lower limb injury

With lower limb injury continuing to rise, lower limb MSK injuries remain a significant problem with elite and amateur athletic populations of both genders through a variety of sports, with around 50% of injuries sustained occurring within the lower limb (Hootman, Dick and Agel, 2007; Schurr *et al.*, 2017; Whittaker *et al.*, 2017; Thorborg *et al.*, 2018), with the cost of such injuries, on both financial, athlete development and player availability being well documented (Bakken *et al.*, 2016). Movement quality has been widely associated with the potential risk of injury. Due to the increased costs (both financial and time-related) of MSK injury within the general and sporting populations, there has been a paradigm shift from reactive intervention towards pro-active prevention. Subsequent research and clinicians have graduated towards addressing modifiable factors (such as capacity, muscle weakness, strength) as well as the identification of higher-risk individuals that enables more directed targeting of preventative rehabilitation and conditioning programming. The genesis of movement assessment tools was initially for identification of biomechanical deficits; however, their incorrect adoption as diagnostic screening tools has potentially become wrongly established. At present, there is low quality, conflicting evidence that has identified strong relationships between injury and specific movement quality outcomes.

A recent systematic review by Whittaker *et al.*, (2017) deduced that evidence of poor or suboptimal movement quality linked to injury remained highly inconsistent in its quality, however, extensive high-quality research continues to show associations between movement variability and MSK injury between injured and uninjured populations (Baida *et al.*, 2018).

Neuromuscular Control (NMC)

Neuromuscular control, or the body's ability to contract the correct muscles to stabilise during movements, has been demonstrated to be an integral component of hip, knee and ankle injuries (Casartelli *et al.*, 2015; Mason-Mackay, Whatman and Reid, 2017; Tamura *et al.*, 2017; Whittaker *et al.*, 2017; Thorborg *et al.*, 2018). Aberrant and poor NMC of the lower limb is frequently viewed as modifiable and has dictated neuromuscular rehabilitation and conditioning programmes in those who demonstrate reduced NMC (Stickler, Finley and Gulgin, 2015; Comfort, Colclough and Herrington, 2016; Fort-Vanmeerhaeghe *et al.*, 2017), to impact injury reduction and risk. Modified NMC has been identified as a fundamental component of LL injuries during static (e.g. squatting) and dynamic (hopping, landing, change of direction) movement patterns (Myer *et al.*, 2008; Munro, Herrington and Carolan, 2012; Hewett *et al.*, 2015; Zebis *et al.*, 2016; Bonato, Benis and La Torre, 2018). Prospective research assessing neuromuscular function has suggested NMC is a significant causal factor for injury, with changes in trunk lean and valgus knee movements under load, linked to ACL injury (Zazulak *et al.*, 2007; Hewett and Myer, 2011; Dingenen *et al.*, 2014). Previous literature has indicated that NMC deficits lead to a cascade of events that attributes to compensatory movement strategies and altered movement patterns that increase the risk of injury (Hewett *et al.*, 2005; Paterno *et al.*, 2010; Padua *et al.*, 2015). Within the literature NMC deficits have been described as presenting as poor landing mechanics, inadequate postural control, and adapted muscle activation stemming from central nervous system changes that negatively affect skeletal muscle control (Lepley *et al.*, 2017).

NMC has also been identified as a factor of injury risk in youth athletes (Quatman-Yates *et al.*, 2012; Read *et al.*, 2016; Soligard *et al.*, 2016; DiCesare, Montalvo, Barber Foss, Thomas, Hewett, *et al.*, 2019; Ellenberger *et al.*, 2020). Injury mechanisms have been described in the literature as occurring at the tissue (tissues ability to tolerate a load) or athlete-level (elements such as NMC, technique and decision making that are impacted by fatigue) (Dye, 2005; Soligard *et al.*, 2016). Maturation of the skeletal and osseous systems in an adolescent is asynchronous with non-linear development of anatomical body segments (Quatman-Yates *et al.*, 2012; Difiori *et al.*, 2014; Malina, 2014; Cumming *et al.*, 2017). Due to potential periods of rapid growth encountered by the developing athlete, it is plausible that they will have different susceptibility to both tissue and athlete level injury mechanism to that identified in adults. It is therefore important to understand the relationships between profiling and changing NMC in relation to the nuances of adolescences, in order to further understand risks to performance and injury.

Practitioners appear to have implemented injury prevention strategies that address one or two factors of movement control within a movement pattern, with the aim of addressing post injury NMC deficits prior to full return to play for an athlete. It appears that factors associated with NMC are an important consideration for development of prospective research of injury prevention strategies, understanding kinematic elements of movement quality will be further regarded below. To meet current literature gaps in both the adult and adolescent, this will include consideration of the trunk and upper limb in addition to the anticipated parameters of the lower limb, to support whole movement pattern evaluation.

Ankle Dorsiflexion

Limitations in ankle dorsiflexion (DF) have been allied to acute and chronic ankle injuries (Mann *et al.*, 2013) such as ankle sprain, impingement, and instability, as well as an increase in knee valgus which has also been shown as a risk factor for injury genesis at the knee (Lersch *et al.*, 2012; Mason-Mackay, Whatman and Reid, 2017; Räisänen *et al.*, 2018b). There are various trains of thought regarding restrictions in ankle DF and subsequent impacts on an injury, such as compensated lowering during squat movements of the centre of mass as the leg remains unable to pass over the foot (Mason-Mackay, Whatman and Reid, 2017). Altered lower extremity landing forces and stiffness have also been demonstrated in dorsiflexion restricted individuals (Leppänen, Pasanen, Krosshaug, *et al.*, 2017a) resulting in reduced loading rates and ground reaction forces.

Literature in relation to the role of DF in the youth athlete is scarce, however in a yearlong prospective study (Backman and Danielson, 2011) reduced ankle DF range during jumping and landing was identified as a risk factor for the development of patella tendinopathy in elite junior basketball players. Limitations in ankle DF maybe attributable to calf musculature tightness (Mason-Mackay, Whatman and Reid, 2017) but it may also occur with inherent ankle joint stiffness (Hirata, Yamadera and Akagi, 2020). Due to the non-sequential development of the skeletal and muscular systems during growth (Quatman-Yates *et al.*, 2012; Difiori *et al.*, 2014) an adolescent athlete may experience both tightness and alterations in ankle stiffness. Unlike an older adult athlete where a causal mechanism is likely to be age related atrophy (Hirata, Yamadera and Akagi, 2020), within the developing youth athlete alterations to DF are more likely attributable to an underdeveloped ankle strategy (Quatman-Yates *et al.*, 2012; Estevan *et al.*, 2020). Therefore, DF maybe a variable of interest to practitioners because of the natural change of a maturing strategy associated with growth.

Resultantly, a change in DF may push individuals into varying alternative movement patterns considered synonymous with specific injuries - resulting in a whole compensated mechanical pattern rather than a restricted movement through a particular joint. Although potentially caused by different underlying mechanisms, DF changes may also play a part in the alteration of adult and adolescent landing mechanics, in a way that influences that individual's predisposition to injury. Its inclusion of investigation for restriction on the whole mechanical movement pattern is warranted.

Knee Flexion

Knee flexion angles are typically viewed in the sagittal plane (Dingenen *et al.*, 2015) and have been associated with ACL injuries due to injury mechanisms occurring near full extension. Reduced knee flexion is also associated with stiffer landings and higher ground reaction forces which alters the load placed through the ACL (Leppänen, Pasanen, Kujala, *et al.*, 2017; Scholtes and Salsich, 2017), as this limitation in sagittal plane range is believed to directly increase the frontal plane load (Pollard, Sigward and Powers, 2010).

Males typically land on a 25-35° flexed knee, which is 5-10° more than females (Leppänen, Pasanen, Krosshaug, *et al.*, 2017b), this suggests that females have to endure increased loads through the knee, with research showing that female athletes are more susceptible to ACL injury than their male counterparts (Hägglund, Waldén and Ekstrand, 2009). Prospective studies that investigate knee flexion angle from the sagittal plane appear minimal, with only one study (Leppänen, Pasanen, Kujala, *et al.*, 2017) found that investigates the relationship between knee flexion angle and ACL injury risk in an adolescent cohort. As with the adult population, Leppänen, Pasanen, Kujala, *et al.*, (2017) demonstrated that low knee flexion angles linked with stiff landings were associated with the risk of ACL injury in young female basketball and floorball players. Although the study has a large sample size, athletes were categorised via chronological age not maturational age. With the average age of a participant recorded at 15.4 years, it is possible that the female participants had completed a growth spurt. It is still unknown if these results can be generalised to other participants such as pre-pubertal athletes, or how the variable of knee flexion maybe impacted by timing or tempo of maturation.

Maximal knee joint flexion is the most substantial predictor of symptomatic patella tendinopathy, with repetitive landing associated with altered lower limb landing strategies identified as a primary causal mechanism (Mann *et al.*, 2013), knee flexion angles may provide a method to identify these at-risk more successfully. In conclusion, altered knee flexion angles detected during single-leg loading may contribute to a knee injury in both the adult and adolescent, and hence are worthy of consideration in movement quality.

Dynamic Knee Valgus (DKV)

Dynamic valgus at the knee is a global term for a combination of lower limb movements (Hip Abduction, Internal Rotation, Knee Abduction, External Tibial Rotation, Foot Pronation) and is considered a movement pattern associated with ACL and PFJ injury (Tamura *et al.*, 2017). This movement action is considered particularly important during the deceleration phase of landing, as suboptimal dynamic alignment can result in reductions in capacity to attenuate the impact forces of landing – altering force distribution at the knee – which is a factor frequently associated with knee injuries (Majewski, Susanne and Klaus, 2006; Mendonça *et al.*, 2015).

A recent study by (Gwynne and Curran, 2018), has confirmed the correlation between DKV and those with PFPS. The author suggests that excessive frontal plane knee alignment had fair specificity and sensitivity of discriminating PFP during SLS movements. ACL patients have also been shown as having increased DKV, in a study of 291 female high school athletes (Numata *et al.*, 2018), DKV was noted as significantly greater in those who went on to sustain ACL injuries over a 3-year observational period compared to those who remained non-injured, the authors suggest that the worse dynamic knee valgus was a potential risk factor in ACL injury in female high school athletes.

As already mentioned DKV is a tri-planer motion, and to thoroughly acknowledge its role in injury risk both the hip and knee have to be considered (Sorenson *et al.*, 2015). The DKV position can be measured quantitatively via 2D and 3D motion analysis (Ageberg *et al.*, 2010; Munro, Herrington and Carolan, 2012; Sorenson *et al.*, 2015; J. Smith *et al.*, 2017), however due to the complexities and non-accessible nature of 3D technology, and the limitations of 2D in capturing motions that are not uniplanar, a valid and reliable visual observation test that can identify DKV on large groups of people is required.

Hip – Internal Rotation (IR)

Hip IR has been reported as a contributing factor to DKV (Powers, 2010; Munro, Herrington and Comfort, 2017) and has been linked to many lower limb injuries such as FAI (Lynch, Bedi, and Larson 2017), ACL and PFPS (Mann *et al.*, 2013; Sorenson *et al.*, 2015; Tamura *et al.*, 2017) back and abdominal Injuries (Camp *et al.*, 2018) and even fifth metatarsal stress fractures (Saita *et al.*, 2018).

IR of the femur results in external rotation of the tibia at the knee joint which can potentially lead to ACL impingement between the femoral condyles structures, as well as disruptions to the PFJ and patella alignment as the lateral aspects of the condyles and facets are affected by contact pressures (Powers, 2010; Sorenson *et al.*, 2015; Tamura *et al.*, 2017). VandenBerg *et al.*, (2017) noted that there was a correlation between hip restricted IR and increased risk of ACL injury – along with a relationship between ACL injury and CAM and pincer FAI morphology in the generalised population and males and female athletes.

Whilst the course of hip deformity is not well understood, and morphological variations conjoined with dynamic hip pain is common in young athletes, there is growing evidence that suggests that CAM deformities can be stimulated by the sports-specific rotation forces on the physis and repetitive high loading of these patterns during growth, which alters the mechanical stimulus of the hip joint attributing to developmental growth alterations and subsequent non-physiologic femoral head remodelling (Casartelli *et al.*, 2015).

High-speed motion capture has been used to capture the range of hip motion via sagittal view to quantify movement in those with FAI (Sheean *et al.*, 2017), these methods, however, are difficult to replicate in the clinical environment due to technological requirements, simpler objective measures such as visual assessment are therefore necessary to begin to classify asymptomatic movement pattern characteristics with those that may develop in FAI, as well as to evaluate those with potential ACL and PFJ involvement.

Hip Adduction

Hip Adduction as a stand-alone measure is not thought to affect injury risk, however, when linked to DKV it is believed to be an impactive factor on injury genesis. Willson and Davis, (2008) correlated DKV to hip adduction during 2D FPPA, it has also been noted in healthy females that hip adduction strength accounts for 22% of the observed variation in FPPA during the single-leg squat (Stickler, Finley and Gulgin, 2015), athletic females that demonstrated superior hip external rotator strength also demonstrate superior dynamic control of the lower limb during unplanned cutting and landing tasks (Malloy *et al.*, 2016), suggesting that observed identification increases in hip adduction are important to understand the role this pattern plays in those athletes involved in cutting and landing.

Pelvic Drop and Trunk Lean

Only a limited number of studies have investigated trunk and pelvic position during movement assessment tasks (Mann *et al.*, 2013; Dingenen *et al.*, 2014; Myer, Bates, *et al.*, 2015; Plummer *et al.*, 2018). During overhead activities, the hip and trunk segments of the body are believed to contribute to 50% of the force and kinetic energy required (Dingenen, Staes, *et al.*, 2018). Understanding the role of the trunk and pelvis during different movement patterns in relation to generation and transfer of force between the lower and upper extremity, as well as identifying those that demonstrated suboptimal trunk motion and postural control during movement patterns is therefore important.

In support of this assertion, Plummer *et al.*, (2018) found that trunk lean assessed via 3D during a SLS moderately correlated with trunk lean during pitching in youth baseball athletes, that corresponded to shoulder and elbow movements associated with an injury. Youth footballers have exhibited significant increase in lateral trunk lean during unilateral landings at the post-pubescent phase of maturation (Read *et al.*, 2018). Another recent study has confirmed decreases in contralateral and increased forward trunk lean in participants who have undergone ACLR correlating to greater hamstring force, with the authors suggesting that participants had to increase trunk stiffness and increase hamstring force to potentially reduce anterior tibial translation (Boggess *et al.*, 2018). Whilst the group did not measure tibial movements specifically it has demonstrated a potential link between the knee and trunk in frontal and sagittal planes. Movement patterns could also be impacted by growth spurt related changes in torso length and centre of mass (Difiori *et al.*, 2014), and as such greater exploration around the impact of growth and maturation on unilateral task performance is required.

A final potential influencing factor to trunk lean, pelvic tilt, pelvic rotation and hip adduction is muscular fatigue at the local level. Following a fatiguing exercise protocol, 60 healthy men and women demonstrated increased lateral and frontal trunk flexion and movements at the hip during a SLS movement test, interestingly the authors did not observe any dynamic valgus patterns at the knee, with the effects of gender only occurring at the pelvis, hip and knee not the trunk (Weeks, Carty and Horan, 2015). This suggests that further work is required to evaluate trunk lean during movement assessment tasks to further identify the role of trunk lean in relation to the hip, knee and ankle complex, and any differences between age groups and genders.

Shoulder and the Upper Limb

The relationship between upper limb, trunk and lower limb kinematics remains relatively unclear since trunk and upper limb kinematics in the frontal and sagittal plane do not appear to have been methodically examined with lower limb kinematics, via any 2D, 3D or qualitative method. The majority of work that analyses bilateral or unilateral landings frequently instruct participants to cross their arms over their chests, or maintain their upper extremities at their sides or statically held out to the side, with Gwynne and Curran, (2014) and Schurr *et al.*, (2017) specifically reporting that shoulder position was restricted to assist with balance during SLS testing.

The methodological restriction of shoulder position during movement assessment tests of the lower limb has in-advertently eliminated the observation of normative and or compensatory upper limb movements. During single leg loading and landing, knee and ankle loading is impacted by whole body loading (Maclachlan, White and Reid, 2015; Dingenen, Blandford, *et al.*, 2018), and therefore lower limb function and movement patterns are heavily impacted by body position as a whole, it is therefore not unreasonable to assume that the upper limb will play a contributing role to this. Concerning practical utility, many athletes do not fixate their upper limb when performing cutting, landing or pivoting tasks, especially with equipment-based sports such as netball, basketball, cricket, javelin, when they may be required to catch or throw at the same time as take-off or landing. Within the developing athlete, the use of the upper limb might also be part of the protective motor response referred to as the parachute reflex (Jaiswal and Moranka, 2017; Bennett, Lashley and Golden, 2020), unlike other primitive reflexes the parachute reflex appears to persists into adulthood. Evaluation of the upper limb in the youth athlete should also be of interest to practitioners to further understand the role of the upper limb during central nervous system maturation (Jaiswal and Moranka, 2017) and the growth spurt. It is pertinent to argue therefore that the upper limb should be considered by movement assessment tools and movement assessment tasks as due to its previous exclusion from the bulk of the literature it is difficult to determine if any restrictions at the shoulder and upper limb are a cause of poor movement quality or an effect on the patterns themselves, future research is needed to confirm any links, before any interpretation of what those links might mean in relation to injury risk occurs.

Although lower limb injuries appear to be on the rise, investigation, risk factors, genesis and mechanics, and preventative measures that address the supposed modifiable factors remain the key focus of the research. Whilst papers focus on the “how” restrictions in range or reduction in neuromuscular control at a particular joint have shown relationships to injury, even if these relationships remain quite low. Despite a relatively extensive body of research, there are no distinct links between one single joint area and injury risk, however, each area may make up a larger component of injury risk, so whilst the effect of each area in isolation is important to understand for injury risk, the reductionist approach of the individual impact of an area on movement quality and injury risk is restrictive. Assessment of kinematics normally occurs within a laboratory and has little practical applicability to the clinical environment, and individual evaluation of biomechanical parameters of the lower limb time-consuming and inconclusive, yet each area has demonstrated its value in being investigated in movement quality. Whilst research still maintains there are “risky” lower limb movement patterns during athletic activities which increase the likelihood of lower limb injury, future research, therefore, needs to identify these parameters within a whole pattern to provide observers with a global impression of the movement quality, which better replicates sporting movements and tasks, and would better inform practitioners of what occurs during compensated mechanical patterns rather than information restricted to a particular joint.

2.4.2 Validity and reliability concepts in human movement monitoring and assessment

For movement screening to be practically applicable the measurement quantities of the functional task must be identified. Any tool selected must be reliable – i.e. are the conclusions the same across different assessors and at each application, valid – i.e. measuring what we expect it to measure, internally consistent – i.e. are the same constructs measured and able to detect a change, changes over a period of time such as a training block or a competitive season (Nae *et al.*, 2017; Mokkink *et al.*, 2018).

Batterham and George, (2003) explain reliability as “the quantity of a measure or test that possesses the reproducibility of the same scores repeatedly in the same circumstance.” Based on this premise reliability is imperative for test validity, with inter-rater and intra-rater reliability being considered the most important aspects to further confidence in the validity of any test or tool (Nae *et al.*, 2017). Establishing the reliability of tests, tools and measurements is consequently hugely important, as measures that are contrary from situation to situation inhibit the correct interpretation of research and subsequently impacts on practical applicability.

Validity is described as the accuracy and credibility of a study (Batterham and George, 2003), usually separated into the two components of Internal and External, internal validity implies that measurements are absolutely characteristic of what they measure and that external validity is the amount and actual applicability of the measurements to other populations, settings to the ones selected (Batterham and George, 2003; Nae *et al.*, 2017; Mokkink *et al.*, 2018). It is paramount to establish that any screening method of functional movement test used within clinical practises and the research domain is reliable and valid. To assure that meaningful data can be extrapolated from the movement patterns of functional assessment tasks, the ability of the methods whether qualitative or quantitive must be able to measure the desired parameters and any differences between and within sessions and those undertaking the tests wither as clinicians or participants, to allow for full application within the practical field.

Variability is the main component of human movement, and as such a human being will never replicate the same movement twice (Stergiou and Decker, 2011). All human movement observation has subjective elements, with practitioners' perceptions of human movement heavily influenced by their prior knowledge, interpretation and selectivity. Within human movement analysis means of measurement of validity and reliability vary greatly, and great controversy regarding the capture of human movement variability within the literature is attributable to the methodological approaches selected (Allen, 2007; Stergiou and Decker, 2011).

It has been suggested that studies that intend to measure physiotherapeutic and physical quality outcome measures should include methods that are able to determine sources and sizes of measurement errors within the context of intended use (Allen, 2007). However, traditional measures that provide a linear account (such as standard deviations of the range) provide a description of the range of variability around a fixed central point, which appears to have been wrongly interpreted by literature that analyses human movement as the standard of human performance being set by the mean, so deviations away from the mean become interpreted as pure error (Stergiou and Decker, 2011). Within the greater "real-life" context of human movement, variability seen within a selected movement pattern is not resultant of movement error, but is a normal variation that naturally occurs within human motor performance.

From an evaluation of human movement perspective, when constructing a methodology to address validity practitioners should aim to identify specific movement qualities and select a movement scale that provides the observation and measurement of these exact qualities. For establishment of reliability practitioners should aim to address and demonstrate similar levels of accuracy of rating of these qualities by independent raters.

Recently, three systematic reviews with meta-analysis (Cuchna, Hoch and Hoch, 2016; Bonazza *et al.*, 2017; Moran *et al.*, 2017) evaluated the movement observational tool the functional movement screen (FMS). Across the three reviews, 44 articles were selected for evaluations, only 5 articles considered validity for the methods and were contained within Bonazza *et al.*, (2017) review. Whilst all authors agreed that both intra-rater and inter-rater reliability was moderate to excellent, no conclusive decisions could be provided for the validity of the FMS method. Similar trends of greater reporting on reliability comparative to validity have been noted in other methods of movement analysis from 3D (Ford, Myer and Hewett, 2007; Malfait *et al.*, 2014; Myer, Bates, *et al.*, 2015) to 2D methods (Poulsen and James, 2011; Munro, Herrington and Carolan, 2012; Dingenen *et al.*, 2014).

Interestingly, subsequent research (Maykut *et al.*, 2015; Sorenson *et al.*, 2015; Schurr *et al.*, 2017; Mostaed, Werner and Barrios, 2018) have attempted to validate 2D methods of movement analysis to 3D methods as the perceived fold standard, despite there being minimal research into the validity of 3D technology itself. To date only one systematic review (Maclachlan, White and Reid, 2015) appears to have investigated the validity of observation of human movement to 2D and 3D motion analysis. Only six studies were deemed suitable for inclusion due to methodological disparities, the authors concluded clinically acceptable results of observer ratings during slow-controlled movements but less so for faster more explosive movements.

The smaller numbers of identified studies to examine validity across the human movement literature suggests gaps between the establishment of reliability and the establishment of validity. While the value of human movement assessment and monitoring tools and tasks commences with the establishment of reliability, the tools and tasks are only practically valuable if validity is also established. There is the need to further distinguish between reliability and validity of human movement methods if additional work is to be completed prospectively to examine any interesting relationships with injury preventions strategies and frameworks.

2.4.3 Methods of movement analysis

In the simplest terms, movement assessment tools describe a singular or composite battery of movement tests or tasks, that aim to assess individuals on their physical performance, quality of movement or both. The rationales for such testing frequently underpinned by the desire to assess for increased risk of injury secondary to poor movement quality or reduced capacity, and to extract information to inform exercise and or training recommendations.

Whilst previous research has suggested that movement screening assessment tools has been used for injury prediction, as demonstrated in section 2.3, over the last few years there has been a shift in the rationale of using screening for injury prediction, towards that of evaluating movement quality. Insufficient movement quality is in itself considered a contributing risk factor for injury (Chimera and Warren, 2016), as well as an indicator of an individual's performance capability, and has resulted in the development and adoption of movement assessment tools and frameworks.

It is a logical assumption that the way an individual moves will impact their injury risk, to date there are weak associations between movement assessment scores and injury phenomenon (Bahr, 2016). Injury mechanisms are multifactorial and complex (Bittencourt *et al.*, 2016), research is beginning to acknowledge the affects combinations of risk factors may have on injury risk, but the interactions are still mainly unknown. Age-related alterations in neuromuscular function have been well established within the adult literature, and in an elderly population the natural age-related changes in muscle and tendon stiffness and muscle quality are frequently accountable in impairments of motor performance (Wu *et al.*, 2020). It has also been postulated that adolescent youth populations also experience declines in motor function as they encounter rapid periods of growth, as temporary changes in centre of mass, limb length and joint moments impact coordination and performance of movement tasks (Quatman-Yates *et al.*, 2012; Difiori *et al.*, 2014). Movement assessment tools aim to provide a quantifiable measurement of quality by evaluating an individual's movement abilities, however the ability of current human movement monitoring methods to appropriately recognise and account for age-related motor function continues to be unclear.

Despite the supposed importance of movement quality on load (Hulin *et al.*, 2016; Gabbett and Whiteley, 2017), risk of injury (Soligard *et al.*, 2017; van Dyk *et al.*, 2017), impacts on return to play (Burnham *et al.*, 2016; Hunt *et al.*, 2017), and demonstrations of physical qualities, the "measurements" of movement quality remain highly elusive. This is partly due to terminology and lack of acceptable and standardised definitions of movement quality, with several differing movement assessment tools proposed within the literature, with each comprising different methods of measurement, quantification, descriptors of quality and composition of either a battery of or singular movement tasks.

From a biomechanical perspective there are three main methods for analysis and monitoring human movement within a sports science and medicine context, which are three-dimensional (3D), two-dimensional (2D) and qualitative (human visual observation normally via a pre-determined scoring system). The methods aim to use either kinematic, kinetic or a combination of both data types to collect non-invasive information on the execution of a body's movement pattern. Due to the advancements in technology and process, both 2D and 3D collection methods are frequently viewed as similar, however each method has its own discernible differences notably around calibration and definition of joint angles and as such each method will be discussed independently below.

Three-dimensional (3D) movement analysis

Laboratory based 3-dimensional (3D) movement analysis is considered the gold-standard method for evaluation and monitoring of human movement injury risk factors (Bell *et al.*, 2013; Gwynne and Curran, 2014; Schurr *et al.*, 2017). 3D motion analysis defines body segments through the placement of markers on the skin which provides orientation to movement axes and joint centres of the body so practitioners can evaluate profiling tests and specific mechanisms of injury (Philp *et al.*, 2019). The method can accurately identify forces across joints, determining multi-planar, rotational forces across a variety of tasks in a reliable way (Schurr *et al.*, 2017).

The majority of the literature linking 3D analysis to injury focus on the knee, particularly ACL and ACLR, through identification of specific injury risk factors. Hewett *et al.*, (2005) showed that larger knee abduction moments demonstrated via 3D analysis during a vertical drop jump test were associated with those that went onto develop an ACL injury. Bohn *et al.*, (2016) and colleagues revealed that ACL deficient knees displayed lower external moments during running than ACL intact and healthy control participants. Increases in hip adduction (Myer *et al.*, 2006), trunk range and instability (Zazulak *et al.*, 2007; Hewett and Myer, 2011; Dingenen *et al.*, 2014), and decreases in knee flexion (Leppänen, Pasanen, Krosshaug, *et al.*, 2017a) as assessed by 3D motion analysis have been related to atypical knee loading and greater injury risk. Further work (Myer *et al.*, 2015) also used the same 3D analysis techniques which demonstrated less peak knee abduction moments in young females with patellofemoral pain (PFP) compared to the uninvolved side and healthy control participants.

Although 3D motion analysis systems are considered the gold standard of human movement assessment, the method remains highly time consuming, costly, and largely inaccessible due to the extensive space and equipment required for its use (McLean *et al.*, 2005; Bell *et al.*, 2013; Gwynne and Curran, 2014; Myer, Ford, *et al.*, 2015; Schurr *et al.*, 2017; Mostaed, Werner and Barrios, 2018). Despite identification of specific risk factors of injury, due to the previously mentioned limitations of 3D technology, the 3D methods are severely limited in their large-scale clinical utility.

As such it is argued that as an on-going assessment and monitoring tool of human movement, the 3D limitations are too great to provide the sustainable, long-term data necessary for successful evaluation of links to injury prevention strategies. Due to the complexity of human movement, it is generally postulated that complex 3D methods of analysis are required, with complex methods generally necessitating highly controlled laboratory environments. Which has led to some authors (Colyer *et al.*, 2018) questioning the ecological validity of the 3D method. As a feasible alternative to 3D motion analysis many authors and practitioners have sought to develop 2D methods that capture motion via video camera to analyse various cinematic measures (Gwynne and Curran, 2014).

Two-dimensional (2D) movement analysis

Numerous injury risk factors identified in the 3D literature have been investigated via 2D research with trunk lean (DiCesare *et al.*, 2014; Dingenen *et al.*, 2014, 2015), hip adduction (Almangoush, Herrington and Jones, 2014), dynamic knee valgus (DKV) (Myer *et al.*, 2010; Munro, Herrington and Carolan, 2012), and knee flexion angle (Myer *et al.*, 2010) successfully captured by 2D methods.

2D analysis requires the use of video where a practitioner measures joint angles onto a frame of movement from the film. Similar to the 3D literature, the 2D literature focuses on the knee with a large number of papers concerned with the measurement of dynamic knee valgus (DKV). Biomechanical purists suggest that 2D analysis is not as precise or accurate with quantification as 3D analysis (Gwynne and Curran, 2014) due to the fact that 2D methods capture movement from a sagittal or frontal perspective and are therefore considered unable to measure rotation (Schurr *et al.*, 2017). Due to this, authors have suggested that the rotational elements presented at the tibia, hip and trunk during DKV are not a true representation of those observed in 3D papers (Willson and Davis, 2008; Ageberg *et al.*, 2010). However large numbers of papers have demonstrated sufficient relationships between 2D and 3D movement analysis parameters to suggest 2D motion analysis remains a viable clinical alternative.

An earlier paper by McLean *et al.*, (2005) suggested moderate relationships (r=.58-.64) between 2D and 3D measurements of frontal plane measures of knee valgus in basketball players during step, jump and shuttle run tasks. This is in contrast to later work by Ageberg *et al.*, (2010) demonstrated between group differences of knee valgus as assessed by visual and 2D measurements, however this was not replicated in 3D measurements of knee valgus across the same group of participants.

Further work has corroborated the use of 2D measures as a viable alternative to 3D motion analysis. Strong significant relationships (r^2 =.72) in 2D FPPA measures to 3D measures have been demonstrated in healthy women during single leg drop landings (Sorenson *et al.*, 2015) and in I-pad generated 2D measurements during vertical drop jumps in the frontal and sagittal plane (r=.48-.77) (Belyea *et al.*, 2015). 2D measurements of frontal plane knee valgus has also correlated strongly to 3D methods (r=.64-.78) in a patellofemoral pain (PFP) cohort (Gwynne and Curran, 2014), suggesting that 2D measurements of motion analysis can be successfully used in asymptomatic and symptomatic populations. In addition to knee measurements work by (Dingenen, Barton, *et al.*, 2018) has also shown significant correlation of 2D pelvic drop, hip adduction and femoral adduction to 3D running profiles in an elite athlete cohort.

Subsequent work by (Schurr *et al.*, 2017) advocated the pragmatic use of 2D movement analysis methods from the sagittal plane with strong agreement between 2D and 3D trunk, hip, knee and ankle measurements during unilateral squat tasks. Strong correlations (r=.047-.57) between 3D hip adduction, and hip internal rotation and 3D measurements have been demonstrated in 1 year post-op ACLR patients during step=down tasks, which led the authors to conclude 2D measurements were useful to identify the requirements of NMC interventions at the hip to reduce injury risk (Mostaed, Werner and Barrios, 2018). This is supported in research by Gabor *et al.*, (2014) where 2D measurements of hip and knee flexion significantly correlated (r=.59-.57) to the 3D measurements of healthy college students during vertical drop landing, and in 2D and 3D measurements at the knee during bilateral squatting (Bell *et al.*, 2013).

The literature pertaining to 2D motion analysis has demonstrated strong reliability and the ability of the 2D method to identify injury risk factors of the lower limb in an accessible and affordable way. However, conflicting evidence remains regarding the links of those risk factors specifically to injury. In a recent prospective study (Räisänen *et al.*, 2020) no association was found between 2D frontal plane knee measurements and the sustaining of a non-contact ankle or knee injury in a mixed gender cohort of 364 team sport athletes. The implications of the research were that sing-leg and drop jumps should not be used as a profiling tool for knee or ankle injury risk. Whilst the study analysed FPPA and general lower limb alignment which is a risk factor for some lower limb injuries (Fox *et al.*, 2016). The authors followed a reductionist approach by focusing on one isolated parameter of one body segment. By negating the rest of the kinetic chain, such as evaluation of the trunk (which has also shown to be a risk factor and contributor to FPPA (Myer *et al.*, 2008; Dingenen *et al.*, 2014; Myer, Bates, *et al.*, 2015) it is unlikely that extensive evaluation of risk could have been completed, and therefore the identification of risk of by evaluation of multiple body segments within a whole movement pattern might be a more useful addition to the literature.

Qualitative movement assessment analysis

Following the industry shift away from isolated joint and muscle testing to that of integrated whole pattern evaluation, there has been an increase in the production of a number of movement systems that aim to capture movement quality through multicomponent movement assessment means (Bennett *et al.*, 2017). Although 2D movement analysis has addressed some of the practical barriers associated with technological analysis, it is not without limitation, and further "practitioner friendly," tools have been developed. The benefits of visual observation is that it is quick, affordable, requires minimal equipment and rater training and can be easily applied on mass (Chimera and Warren, 2016).

Unlike the quantitive approach associated with 2D and 3D motion analysis, visual observation and movement profiling systems provide a qualitative element to human movement analysis and monitoring. Where sports medicine practitioners apply a descriptive and categorisation approach without the direct application of measurement of body position (Carlson, Sheehan and Boden, 2016). Information regarding qualitative field-based analysis of human movement is still emerging, with their application to wider clinical practise still being undertaken, therefore a more in-depth investigation into the qualitative design had been included below.

Four qualitative assessment tools (figure 2.8) were identified within the literature, the Functional Movement Screen (FMS), the Landing Error Scoring System (LESS), Soccer Injury Movement Screen (SIMs) and Qualitative Analysis of Singe Leg Loading (QASLS), with each focusing on different populations, assessment objectives and content as part of a group of testing or as a stand-alone metric.

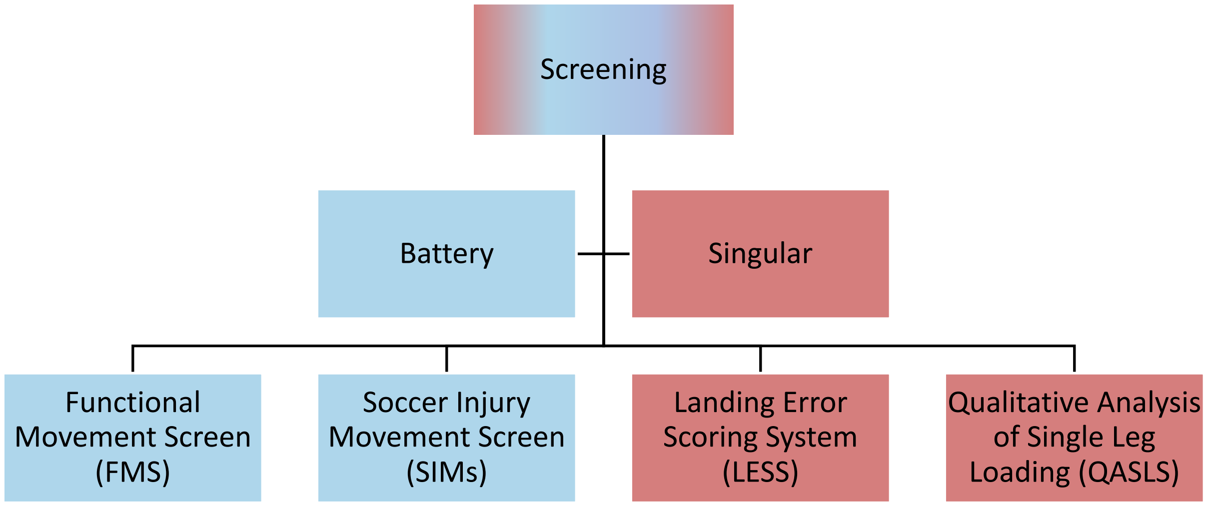


Figure 2.8 Examples of qualitative assessment tools

The Functional Movement Screen (FMS)

The FMS was initially described by Grey Cook (2006) as a means of assessing fundamental human movement in its entirety via 7 key movements and is arguably the first commercial movement competency-based test that has demonstrated great focus within the research (Cook, Burton and Hoogenboom, 2006; Moran *et al.*, 2017). Making use of an ordinal scoring system from 3-0, with 3 being the ideal, each pattern is scored based on the degree of an observed compensatory pattern. The sum of which across all 7 movements is then combined into a composite score. Despite statements from Cook et al., (2006) that the objective of the FMS assessment is to identify muscular and movement dysfunction within a healthy general population. Since reports by Kiesel, Plisky and Voight, (2007) on their American football players, its popularity as in injury prevention tool escalated with many researchers beginning to explore its use as a dichotomised score, and its relationship to MSK injury. Whilst the FMS has been shown as a reliable instrument between raters of differing experience and appears to have good face validity with clinical and sporting movement experts (Chimera and Warren, 2016), several systematic reviews have concluded that FMS composite scores do not provide sufficient levels of evidence or associations to work as an injury prediction tool (Moran *et al.*, 2017).

However, the FMS has been able to identify weaknesses of movement quality within the kinetic chain, this observation of movement quality concerning physical quality may subsequently demonstrate the utility of qualitative movement tools for clinicians when it comes to directing exercise prescription or strength programme interventions. Whilst this adds strength to the argument of further exploring the clinical utility of qualitative methods, the design of the FMS makes it unsuitable for high-performance athletes as the functional tests contained within it does not allow for suitable physical demand encountered within sport (Wilke, Pfeiffer and Froböse, 2017), it will therefore not be included further within this study.

The Soccer Injury Movement Screen (SIMs)

Movement specificity has led to the development of sport-specific tools in an attempt to address the shortcomings of the general movement elements of the FMS, to reflect common anatomical sites and higher-level activity, such as jumping and landing, that are encountered within the sport.

SIMs were designed with the intent to screen athletes specifically from a soccer background, and resultantly contains metrics that focus around 5 key areas that best reflect the types and sites of injuries encountered in football (McCunn *et al.*, 2017). Potentially due to lessons learned around the incorrect conflating of the FMS with predictive capability, the constructors of the SIMs state that SIMs does not predict injury – but proposes associations between movement quality and injury risk via causative relationships. By evaluating the efficacy of the individuals' pattern of movement in relations to strength and function as potential risk factors, SIMs aims to inform subsequent exercise interventions through injury prevention. Work by McCunn *et al.*, (2017) has shown moderate to almost perfect (k = 0.43-0.91) inter-rater values, and compelling evidence for the use of the TJA (k = 0.73). With the use of a composite score, the authors reported substantial (0.63-0.68) weighted kappa values and good ICCs (0.66-0.72) for each rater. These results, similar to the relationships observed in FMS, indicate that composite scores demonstrate acceptable intra-inter rater reliability, but that future research needs to investigate why they provide valid measures of movement quality and subsequent relationships between movement quality, composite scores and potential injury longitudinally.

The Landing Error Scoring System (LESS)

The LESS (Padua *et al.*, 2009) is intended for both sporting and non-sporting populations and unlike the battery-based FMS and SIMs approach focuses on 1 movement of jump landing, but focuses on specific elements of movement quality errors (such as knee flexion angles, hip internal rotation) of the lower limb to identify the increased risk of injury type such as an ACL rupture. A relatively inexpensive assessment tool, that requires filming from the frontal and sagittal planes, the tool has shown good inter & intra rater reliability (Padua *et al.*, 2009, 2011; Onate *et al.*, 2010; Timothy C Mauntel *et al.*, 2013; Chimera and Warren, 2016) and is one of the few qualitative methods that has sought validity (concurrent) were compared to the 3D gold standard (Onate *et al.*, 2010; Mauntel *et al.*, 2017).

Whilst more accessible than the laboratory-based 3D method, the tool is not without fault, the initial 17 item evaluation is lengthy and requires video playback at a later date, adding increased time constraints to its utility practically and increased requirements on assessor training. This may act as a hindrance to implementation, and movement assessment can only be of benefit if they allow information to be collected in a useable way. To enhance its utility the sing leg LESS (SL-LESS) wand LESS- RT (total of 10 errors) were developed but are sparingly reported within the literature. The predictive value of the test also remains paradoxical with some authors citing that scores do predict ACL injury (Everard, Lyons and Harrison, 2018), whilst other research states that it does not (Wilke, Pfeiffer and Froböse, 2017).

The LESS appears to be a reliable tool that is regularly used and well known, however questions around its validity and predictive value remain, in regards to utility the test remains difficult to monitor and despite its intention for multiple populations, is limited to jumping movements only.

Qualitative Analysis of Single-Leg Loading (QASLS)

The QASLS assessment tool is a new assessment tool that includes a simple evaluation scale with a maximum of 2 functional tests – the Single Leg Squat and Single Leg Land (Wilke, Pfeiffer and Froböse, 2017). Based on previous work by (Crossley *et al.*, 2011; Whatman, Hume and Hing, 2013), QASLS utilises a dichotomous scoring system of segmental body regions (Foot, Knee, Thigh, Pelvis, Trunk, Arms) with scoring given to noted movement strategies, the least amount of strategies used to score zero the most amount of strategies used to score 10. It has greater generalisation than the FMS and sports-specific systems such as SIMs, is designed for use within both sporting and non-sporting populations, has the benefits of focusing on kinematic specific movement quality errors similar to the LESS, but has the duality as working as a single stand-alone test – or being included as part of a battery. At present only 2 studies (Almangoush, Herrington and Jones, 2014; Herrington and Munro, 2014) and 1 systematic review (Wilke, Pfeiffer and Froböse, 2017) have attempted to evaluate QASLS. Reliability across senior to expert clinicians is excellent (Percentage of Agreement 83-100%) and intra-rater agreement to almost perfect/excellent (PEA 95-100%, k = 0.89-1.0) (Almangoush, Herrington and Jones, 2014), and similarly strong criterion validity was also demonstrated when compared to the gold standard 3D measurements for both the SLS (PEA 98.4%) and SLL (97.1%). Herrington, Myer and Horsley, (2013) have provided operational definitions and dichotomous scoring instruction for each movement strategy observed at each segmental level, however the authors did not clarify how to determine computation of QASLS compound score between repetitions and from multiple repetitions of movement tasks. Anecdotally, the QASLS profiling system is designed to comprise the total number of strategies required by and individual to complete a movement task irregardless of frequency or number of task repetitions. Previous rater-reliability articles investigating the QASLS tool (Almangoush, Herrington and Jones, 2014; Herrington and Munro, 2014; Horobin and Thawley, 2015) during unilateral squatting and landing tasks presented the number of evaluated repetitions (3 or 5). It was unclear if the authors used the collective "highest" score method, or an average of the 3-5 repetitions to designate the compound QASLS score. The best method for compound QASLS scoring and how that would impact injury risk categorisation has yet to be fully elucidated. It is important for both clinical and academic progress that calculation methods are clear and appropriate across specific populations to improve profiling application and the correct performance inferences.

Whilst the above studies are limited to healthy subjects of university age, the method has shown potential as a conveniently administrable test in both the research and clinical settings potentially across different population groups. Although this evidence strongly suggests that QASLs is a valid and reliable alternative method of visually assessing the lower limb, more research is required to establish reliability and sensitivity to changes in performance longitudinally across a larger number of populations, sporting groups and ages.

Further research into qualitative lower limb visual measures by comparison to technical and other objective methods is required to facilitate the establishment of validity and reliable application. What appears clear from the previously published works is that qualitative assessment has good intra and inter-rater reliability and present a viable alternative to the elaborate and expensive laboratory-based methods and allows for the capturing of rotations that 2D measurements are unable to. Segmental scoring has shown the potential to direct clinicians towards areas of potential weakness that then maybe addressed to improve movement quality, composite scores have demonstrated use in injury prediction – however changes in and within these composite scores has yet to be established, and the relationship these may have to reduce injury risk remains unexplored.

Further work, therefore, should focus on validating qualitative methods (such as QASLS) to current considered gold standard methods, also the establishment of typical performances of QASLS within different populations groups and changes that occur within these performances should be investigated to facilitate understanding of this tool used to capture movement quality and optimise rehabilitation conditioning and return to play programmes.

2.4.4 Movement assessment tasks

The previously discussed movement screening assessment tools comprise different movement assessment tasks that aim to evaluate an individual's quality of movement during a set pattern or task such as landing. Injuries continue to be a significant blight throughout sport from youth to masters age athletes, across the amateur to elite levels as well as within everyday life (Whatman, Hume and Hing, 2013; Maclachlan, White and Reid, 2015; Bennett *et al.*, 2017; Gabbett and Whiteley, 2017).

There will always be great fluctuation in movement quality mainly attributed to anatomical variance (Maclachlan, White and Reid, 2015), and whilst this is broadly acknowledged, reduced movement quality and particular suboptimal lower limb movement patterns (as discussed in 2.4.1) are considered abeyant contributors to lower limb injury. Defective control and alignment are often considered to be influenced by modifiable factors such as neuromuscular control, muscle synergy, weakness and capacity – coupled with a shift within musculoskeletal assessment from evaluation of individual joints and muscles (Bennett *et al.*, 2017), clinicians are moving towards movement assessment tests that consider movement patterns in their absoluteness.

Although there is an increasing onus on the importance of movement quality within the injury risk mitigation and injury prevention literature, movement quality itself remains highly subjective. Subsequently, there is no current recommendations regarding specific movement assessment tasks, with numerous different movement profiling methodologies, and measures and movements contained within literature (Chimera and Warren, 2016; McCunn and Meyer, 2016; Bennett *et al.*, 2017).

Therefore, the predictive ability, injury prevention and risk mitigation efficacy of movement assessment tasks, along with their capabilities to monitor potential physical qualities remains unknown. This section of the review aims to identify and explore commonly used functional movement screening performance tasks, to provide critical appraisal of the reliability and validity of the measurement components. With the exploration of their suggested outcomes and current use in different populations.

Approach to literature review

Systematic and narrative reviews provide different conceptual approaches regarding literature synthesis and review, with strengths and limitations inherent in both. Certain problems require data solutions, others require clarification and insight (Greenhalgh, Thorne and Malterud, 2018), some like the research questions within this thesis require both. Traditional systematic reviews and meta-analysis reviews present probabilistic, generalisable "facts," to aid prediction (Greenhalgh, Thorne and Malterud, 2018), a concept that has previously been identified as problematic within the body of the screening and profiling literature (Sections 2.2-2.3) . Narrative reviews present "plausible" contentions that move beyond the comparing of data to provide interpretation and critical insight (Greenhalgh, Thorne and Malterud, 2018) dispensing wider understanding of a topic through narrative synthesis in a way comparative systematic reporting cannot (Campbell *et al.*, 2020). Narrative reviews can be completed using numerous methodologies that may deviate from traditional methods but are still presented and directed in a systematic way (Greenhalgh, Thorne and Malterud, 2018; Campbell *et al.*, 2020).

To meet the aims of this section of the literature review, evidence from current movement screening performance tasks has been drawn together to highlight methodological challenges to current processes, as well as investigation into why movement has been analysed in a particular way and the impact interpretation may have had. A systematic "process", rather than a systematic "design" has been deliberately chosen, as it is understood that systematic designs involve reductionist predefining of a narrow research question via a highly structured method. However, the term "process" suggests the capture of specific information, but includes the ability to interpret, critique and define reporting on a more global footing (Greenhalgh, Thorne and Malterud, 2018; Campbell *et al.*, 2020). As such, a narrative synthesis was conducted as it was better placed to meet the aims and objectives of the thesis.

Data Sources & Search

A literature search was completed using five online databases no restrictions on publication date were applied to allow for the capture of literature from inception. Databases selected included CINAHL (Cumulative Index to Nursing & Allied Health Literature), Medline, Scopus, SPORTDISCUS and Embase. The same key search terms (Appendix A) used for each search engine are limited to the English language and full-text articles.

Studies were included if they investigated human observation of movement either via 2D or 3D (real-time or video playback) or a combination of both methods during functional tasks. The study population was limited to youth and adult athletes which were described as collegiate, club, recreational, semi-professional, professional or elite level. Studies that included participants with neurological and or other co-morbidities were discounted due to the effects that comprised neuromuscular systems may have on results. Adults were classified as those aged over 18, and youth under 18, due to age-related changes that occur during growth and maturation. Studies were excluded if they involved cadaveric or animal models, or if they were abstracts, editorials or review based (table 2.1).

The search (figure 2.9) yielded 1682 papers, 1262 duplicates were removed leaving 317 papers that were possibly relevant. Studies that did not meet the inclusion criteria (i.e. not human subjects, presented in the English Language, no association between a movement quality outcome, not full article, or included participants that had ineligible conditions and co-morbidities), this was decreased to 64. Overall only 23 studies were deemed suitable for inclusion.

Table 2.1 Inclusion and exclusion criteria

Inclusion Criteria	**Exclusion Criteria**
Human Observation of real-time/video playback of 3D/2D or Qualitative functional tasks	None Human Subjects
	No Movement Quality Outcome Recorded
Lower Limb Functional Assessment Only	Not in the English Language
Healthy Subjects	Unclear association between Movement Quality Outcome and Lower Limb Injury
Observer Levels either Novice, Experienced or Expert	Participants had neurological conditions i.e.: Stroke, Hemiplegia, Spinal Cord Injury, Parkinson's
Reported a movement quality outcome that was either questionnaire based or qualitative	Participants had other co-morbidities i.e. Rheumatoid Arthritis, Osteoporosis, Cancer
	Abstracts Only, Reviews, Case Studies

Limitations

Of the 23 studies selected due to inconsistency within the methodological design, population heterogeneity, movement tasks selected and outcomes used to record movement quality, assumptions for a quantitive meta-analysis review were precluded. Despite a comprehensively selected search strategy, the inclusion of English only articles may have adverted inclusion of relevant articles in other languages.

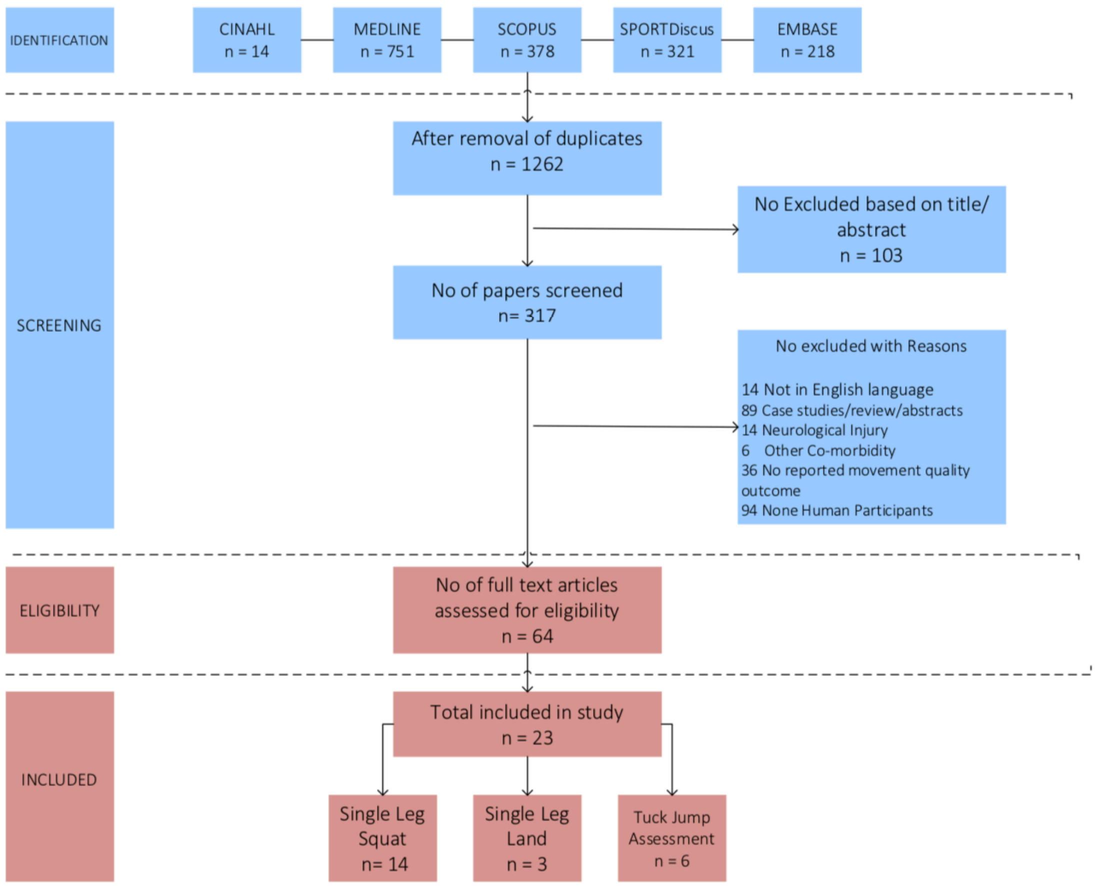


Figure 2.9 Flow chart of study selection

The assessment of functional all-encompassing movement tasks such as squats, single leg squats and drop jumps, which is by far the most reported screening tests within the literature – have been reported as valid and reliable (Whatman, Hume and Hing, 2013; Schurr *et al.*, 2017; Barker-Davies *et al.*, 2018), and are a frequent component to lower limb screening. The majority of these tests are bilateral, with the scrutiny of unilateral landings less reported within the literature. Unilateral tests such as SLS and SLL have been proclaimed as more representative of landing and sporting movement patterns such as decelerating and pivoting techniques, that result in overuse and traumatic injuries. Despite their prevalence of use in practise their reliability and validity have not been well defined. Movement assessment tests aim to provide clinical quantification of lower limb function. Due to this and the fact that they may be evaluated via qualitative assessment tools the single leg squat, single leg land and tuck jump assessment have been selected and will be discussed more below.

Single Leg Squats (SLS) (Table 2.2)

The Single Leg Squat (SLS) is a clinical test frequently used within physiotherapy as a simple method of observing a patient's movement pattern to identify an abnormality such as a dynamic knee valgus, to then better inform a diagnosis. Participants perform the task standing on one leg and squatting as far as possible or to a predetermined range or to symptom diagnosis. It is frequently employed by clinicians within a sporting and clinical setting as a lower level substitute or pre-requisite for higher level efforts such as jumping or running that are unable to be completed due to participants experiencing lower limb pain, or because of restrictions within available testing space.

SLS pattern is a pattern that both sporting and general populations access consistently and repetitively, requires control of the torso and upper body over a stationed leg and flexion of a loaded hip and knee (Edmondston *et al.*, 2013; Raïsänen *et al.*, 2016) in a way that replicates many day to day tasks – such as stair ascent – as well as during athletic activity such as change of direction and landing. Practitioners also utilised comparisons of limb to limb differences particularly in participants that are presenting with pain or pathology to establish if observed abnormal biomechanics or movement are indicative of muscle weakness, endurance or sub-standard motor-control.

Similar to other movement tests the successful practical applicability of any observed findings depends on the abilities of the observer during the exam. Intra and Inter-rater reliability of the SLS method has been demonstrated extensively within the literature across a range of clinician experience (Poulsen and James, 2011; Weeks, Carty and Horan, 2012; Almangoush, Herrington and Jones, 2014; Tate *et al.*, 2015; Raïsänen *et al.*, 2016), within these studies both novice level rater and experienced level raters have demonstrated reliable use of the SLS tool, suggesting that practitioners of all abilities can identify inadequate movement patterns, however, all the participants included within the previous studies were selected from a healthy cohort, and it is unclear if the exclusion of those with lower limb pathology is a limitation.

Within-session and between-session reliability have been assessed (Herrington et al. 2017; Munro, Herrington, and Carolan 2012), although to a lesser extent with a focus being around

FPPA and hip adduction. Reported ICC values have ranged from 0.59-0.88 for within-session and 0.72-0.91 for between-session for both variables. However, these studies remained focused on the frontal plane capture with no data or evaluation provided for sagittal plane kinematic parameters or for the trunk, upper limb motion. Given the potential importance that trunk and upper limb position may present to lower limb biomechanics, and that the majority of studies have retained a focus around the knee negating the relationship of what may be occurring distally or proximally within the kinetic chain, for these reasons the reliability of the SLS requires visitation.

Despite its exposure within the literature, no standard method of the single leg squat is described, with different methods of a squat task becoming evident, similarly authors choose to evaluate the task via a range of visual, video and 3D motion analysis all of which will influence its reliability, and make comparisons between papers hugely intricate. Initial pioneers of the SLS exercise saw its development into a test. Liebenson (2002) initially utilised an ordinal method of analysis of movement sign and dysfunction, which was subsequently developed into a performance scale of Excellent, Good, Fair or Poor that promoted specific cut-off points as markers (Bailey, Selfe and Richards, 2011). The limitations of both methods around pelvic position, shoulder position, supported/unsupported test position and duration of squat, as well as the limitation of the cut off of joint position, have led to the attribution of many practitioners failing to fully describe their methods used, authors report using one of the above methods but are actually modifications, or the adaptation of the method to meet their own needs, which further confounds inter-study interpretation.

The depth of the squat as deduced by knee flexion varies between papers, Edmondston et al. (2013) requested participants squat to 30°, whereas Räisänen et al. (2016) selected 90°, other reported ranges were 45° (Herrington et al. 2017; Munro, Herrington, and Carolan 2012; Poulsen and James 2011) 50°(Ageberg *et al.*, 2010), 60° (Gwynne and Curran, 2014; Harris-Hayes *et al.*, 2014; Barker-Davies *et al.*, 2018) 75° (Dingenen *et al.*, 2014) and Schurr et al. (2017) encouraging participants to squat as far as possible. Hip flexion reduces the movement arm of the gluteus medius and increases reduced hip abduction torque, as hip flexion increases knee flexion, studies that select greater knee flexion may induce greater pelvic drop that is easier to observe and this effects observation interpretation and reliability. Whilst the standardisations of protocols are considered integral to research design, in relation to practical application within a real-world context – consistent organisation of knee flexion position requires extra equipment and extra time that may not be available within the clinical scenarios and thus accurate compliance to a set range within day to day practise is unlikely. A selected knee flexion angle may offer a significant challenge to one individual and not another, and again may not adequately represent the specificity of a sport where an athlete may regularly squat to within a certain range.

Similarly, many researchers have restricted shoulder position to assist with balance during testing. Gwynne and Curran, (2014) used 2D analysis of FPPA compared to 3D motion analysis within 18 subjects during SLS. By doing so demonstrated good correlations at the knee in the frontal plane between 2D & 3D analysis (r = 0.64 – 0.78). This was further expanded by Schurr et al. (2017) whom further evaluated sagittal plane movement and deduced that 2D capture was comparable to 3D during the evaluation of joint displacement within the sagittal plane (r = 0.51-0.93). Whilst both papers use the foot, knee, pelvis and hip positions associated with lower limb movements, by encouraging their subjects to keep the arms across their chests could have benefited trunk control subsequently altering atypical movement at the hip and knee thus eliminated the opportunity for observations and capturing of any deviations in trunk or upper limb strategies.

Throughout the SLS knee loading is resultant of whole body loading (Dingenen *et al.*, 2014), therefore lower limb function is highly influenced by the trunk, upper limb and body positioning as a whole, and accordingly the lack of inclusion of observation of trunk and upper limb movement means these studies as yet are not fully understood and require further consideration.

All studies selected utalised 2D analysis to assess frontal plane kinematics, with only four studies selecting a visual assessment observational tool as a movement quality outcome (Ageberg *et al.*, 2010; Poulsen and James, 2011; Weeks, Carty and Horan, 2012; Almangoush, Herrington and Jones, 2014). Although visual rating is common in clinical practise, however, the reported reliability and validity of visual ratings remains hugely variable. Similar to there being no standard methods of single leg squat, visual observational ratings are also inconsistent. The 4 studies used segmental methods of scoring anatomical regions, however, each adopts a different approach and different regions. The best inter and intra-rater agreement has been reported by Almangoush et al. (2014) (k = 0.63 –1.0, PEA 83-100%) who used QASLS dichotomous scoring system of 10 tasks across size segmental regions (Arm, Trunk, Pelvis, Thigh, Knee, Stance).

The major limitations of this study is the small sample size and that ratings were only noted within a frontal view, comparable levels of agreement (PEA 96%, k = 0.92) was also demonstrated by Ageberg et al. (2010) whom chose to also use dichotomous scoring, however limited themselves to just the anatomical regions of the knee and used highly experienced clinicians whom had received extensive training, which is likely to have attributed to the high levels of reported agreement. Almangoush et al. (2014) raters received no training in the visual methods. Poulsen and James (2011), again had minimal rater training and selected a more complex multi-segmental rating modified from (Chmielewski *et al.*, 2007) methods, which reported similar inter-rater agreement between six novice physiotherapy students (r = 0.88–0.98). Intra-rater reliability has again been shown as good to excellent for student and experienced physiotherapists (ICC = 0.71-0.81) (Weeks, Carty and Horan, 2012), however, as per all the other studies participants selected for this study were limited to healthy individuals between the ages of 18-37 years. The results of all these studies demonstrate that visual rating tools can be successfully utilised across a range of clinical practise experience, there is no research to date regarding the use of these tools within other disciplines such as sports coaching or strength and conditioning.

More constructive analysis into the SLS considering more anatomical regions such as the upper limb and trunk position has not been extensively investigated, the reliability and validity of the SLS by visual assessment has been confined to a limited age group. It is clear that future research is required into the reliability and validity of the SLS across different age groups, athletic populations and during different phases of growth, as this, in turn, may contribute to the specific mechanisms and presentations of undesired lower limb movement, as well as assist with more consistent methodological considerations for research.

Table: 2.2 Summary of studies analysing Single Leg Squat

Study	Sport	Method of Analysis	Functional Test/Test Battery	Movement Quality Outcomes	Reliability Reported	Validity Reported
Ageburg (2010)	Normal Population	2D/3D	Mini SLS Frontal Plane View	"Observational Knees over toes" 3D – peak knee flexion	Inter-Rater - via kappa coefficient 0.92 (95% CI0.75-1.08) P= 0.317 no sig diff 96%	2D- peak tibial, peak thigh, peak knee Varus/valgus angles degrees. 3D- peak hip IR/ER angle, peak knee Varus/valgus angle (degrees)
Alamangoush (2014)	University Population – no sport listed	2D	SLS	QASLS	Intra & Inter-Observer reliability, PEA all subjects ranged 83-100% with k=0.63 to 1.0, Intra 95-10% kappa values of k=0.89-1.0	Proposes content validity
Barker-Davies (2018)	Non-Injured Military Recruits	2D/3D	SLS, Small Knee bend Single Leg Decline Squat	3D compared to an observational score of squat depth, hip adduction, pelvic obliquity, pelvic tilt and trunk flexion summated into a composite score	Hip add & trunk flexion moderate - substantial inter- and intra-rater reliability (range κ=0.408–0.699) other criteria mostly fair (κ≤0.4). Composite scores inter-rater reliability were ICC(1,1)=0.419 & ICC(1,κ)=0.783 &intra-rater reliability were ICC(1,1)=0.672 & κ(w)=0.526.	Individual raters vs Kinematic data was poor to fair
Dinengen (2014)	Soccer, Handball, Volleyball	2D/3D (only for SLDVJ)	SLS, Single Leg Drop, Vertical Jump	Knee Valgus Lateral Trunk Motion	Between and within testers not for test-retest Excellent ICC for the LTM angle was found within (0.99-1.00) and between testers (0.98 -0.99). The sum of KV and LTM was significantly correlated with the pKAM during the SLDVJ for the dominant (r =-0.36; p =0.017) and non-dominant leg (r =-0.32; p =0.034), while either angle alone was not.	No
Edmondston (2013)	University competitive sport	2D	SLS Single Leg Stance Hip Hitch Hip drop	trunk and pelvic angle femoral pelvic angle trunk lean angle	Excellent agreement (87-93%) for the direction of trunk movement between observers, and between observational and quantitative analysis (80 -96%) was established for the single leg squat test. Also included within and between sides data	No
Gwynne (2014)	Recreationally active	2D/3D	SLS	FPPA	ICC, SEM and CI	No
Harris-Hayes (2014)	University Athletics	2D	SLS	FPPA Own qualitative method Valgus/None/Varus	Intra - Inter-Rater via K-Values - substantial to excellent, PEA visual Ax & Quantitive FPPA 90% K value 0.85	? Construct Validity compared visual scale to FPPA did not mention as validity
Herrington (2017)	University Healthy Population	2D/3D	SLS SLL	FPPA HADD	Inter-tester reliability SLS & SLL. FPPA & HADD show excellent correlations (ICC2,1 0.97–0.99). Within & between day Ax LS & SLL showed good to excellent	Criterion Validity of 2D against 3D via correlation FPPA of SLS r= 0.79, p= 0.008.

					correlations (ICC: 0.72–91). 2D FPPA measures good correlation to knee abn angle in 3-D in SLS (r = 0.79, p = 0.008) & to knee abduction moment (r = 0.65, p = 0.009). 2D HADD very good correlation with 3D HADD during SLS (r = 0.81, p = 0.001), good correlation during SLL (r = 0.62, p = 0.013).	HADD of SLS. r= 0.81, p = 0.001 HADD of SLL r=0.62, p =0.013
Munro (2012)	Recreationally active	2D	SLS Drop Jump SLL	FPPA	Within-day ICCs good reliability range .59 to .88, between-days ICCs good to excellent, range.72 to .91. SEM & SDD values range 2.72° to 3.01° and 7.54° to 8.93°	Eluded been proven before by other research no actual results to prove in this study
Poulson (2011)	Does not say	2D	SLS	FPPA Modified Ordinal Scale from Chmielewski (2007) methods	Interrater reliability of ordinal scale measures kappa coefficient 95% CI 0.68 (0.46–0.87). Interrater reliability FPPA range 0.88 to 0.98. Interrater reliability FPPA 95% CI was 0.99 (0.97–1.00).	No
Raisnen (2016)	Floorball Basketball Ice Hockey Volleyball	2D	SLS	FPPA	Intra rater reliability K - values fair- very good over 3 years 0.28-0.89. Inter-rater reliability K-values poor-fair 0.16-0.32	No
Schurr (2017)	Recreationally active	2D/3D	SLS	Trunk, Hip, Knee and Ankle Kinematic values	Correlation coefficients	No
Tait (2015)	Does not say	2D	SLS	FPPA	Intra Tester Reliability 0/91-0.94 (0.78-0.98) Test-Retest Reliability FPPA rated Excellent (Inter Tester novice & expert. 0.92-0.96 ICC 95% CI 0.81-0.99)	No
Weeks (2012)	Generally healthy	2D/3D	SLS	Hip and Knee Kinematics compared to dichotomous good or bed rating	Inter-rater reliability good for physiotherapists (ICC3,1 = 0.71) & students (ICC3,1 = 0.60) Intra-rater reliability was excellent for physiotherapists (ICC3,1 = 0.81) good for students (ICC3,1 = 0.71).	No

2D – Two-dimension, 3D – Three Dimensional, FPPA – Frontal Plane Projection Angle, HADD – Hip Adduction Angle, ICC- Intraclass Correlation, PEA – Percentage of exact agreement, SLDVJ – Single-Leg Drop Vertical Jump, SLL – Single Leg Land, SLS – Single Leg Squat

Single-Leg Land (SLL) (Table 2.3)

Drop Jump tasks have been wildly investigated within the literature on account of associated risks of ACL and PFJ injury from increased knee valgus motion observed during this task (Maclachlan, White and Reid, 2015; Bennett *et al.*, 2017). Whilst the bilateral element of these landings has received great attention in relation to injury mechanism, unliteral landings are more indicative of traumatic and overuse injuries within the lower limb (Whatman, Hume and Hing, 2013). During landing, if an individual who cannot access the appropriate hip flexion will depend troublesomely on frontal plane moments to decelerate their centre of mass landing forces (Schurr *et al.*, 2017), the SLL is arguably, therefore, a more relevant tool as it replicated unilateral landing techniques observed across all ranges and abilities of sports.

One author (Taylor *et al.*, 2016) documented the use of a single-leg landing task within recreationally active females. Procedures for the unliteral jump landing tasks required participants jump onto a force-plate from a distance of one-half of their leg length away. Despite classification of this task as a landing task by the authors, the action appeared more replicative of a hop landing. Due to potential differences in a horizontal transition to landing, comparative to a vertical transition landing (Kockum and Heijne, 2015), to keep consistency of methodological analysis, studies that included single-leg “hop” landings were further discarded from consideration within this review.

The SLL has previously been used to investigate the reliability of 2D FPPA and hip adduction angles (Munro, Herrington and Carolan, 2012; Herrington *et al.*, 2017), however, its use is limited to three studies (Munro, Herrington and Carolan, 2012; Herrington *et al.*, 2017; Munro, Herrington and Comfort, 2017). The SLL has shown good (ICC = 0.75 - 0.79) within-session and between-session (ICC = 0.80- 0.82) reliability in university-aged male and female subjects (Munro, Herrington and Carolan, 2012) and similar inter-rater reliability (ICC = 0.99-0.99) when measuring FPPA and Hip Adduction (HADD) has also been demonstrated. Herrington et al. (2017) found a good relationship of HADD angle between 2D and 3D SLL parameters (r = 0.62, p = 0.013) suggesting that 2D motion analysis reasonably epitomizes with 3D motion capture parameters. Whilst 3D measures are regarded as the gold standard for movement analysis (Bohn *et al.*, 2016) and Herrington *et al.*, (2017) has demonstrated evidence of criterion validity, beyond this paper no other validity for the SLL via 2D or qualitative means has been reported, and therefore further investigation of the validity of the SLL as a screening tool is required. Ageberg *et al.*, (2010) and Whatman, Hume and Hing, (2013) have provided evidence that knee and pelvic 2D kinematics are better determined by visual observation, although several studies have selected visual observation and qualitative assessment tools to evaluate the SLS performance (Ageberg *et al.*, 2010; Poulsen and James, 2011; Weeks, Carty and Horan, 2012; Almangoush, Herrington and Jones, 2014) it appears no previous work has been undertaken to evaluate intra-tester, between and within qualitative means or beyond the 2D kinematic parameters of FPPA and HADD angles. As previously mentioned, given the importance of unilateral deceleration of landing forces in the sagittal plane, additional investigation into the SLL other than the frontal view is also warranted.

Table: 2.3 Summary of studies analysing Single Leg Land

Study	Sport	Method of Analysis	Functional Test/Test Battery	Movement Quality Outcomes	Reliability Reported	Validity Reported
Herrington (2017)	University Healthy Population	2D/3D	SLS SLL	FPPA HADD	Inter-tester reliability SLS & SLL. FPPA & HADD show excellent correlations (ICC2,1 0.97–0.99). Within & between day Ax LS & SLL showed good to excellent correlations (ICC: 0.72–91). 2D FPPA measures good correlation to knee abn angle in 3-D in SLS (r = 0.79, p = 0.008) & to knee abduction moment (r = 0.65, p = 0.009). 2D HADD very good correlation with 3D HADD during SLS (r = 0.81, p = 0.001), good correlation during SLL (r = 0.62, p = 0.013).	Criterion Validity of 2D against 3D via correlation FPPA of SLS r= 0.79, p= 0.008. HADD of SLS. r= 0.81, p = 0.001 HADD of SLL r=0.62, p =0.013
Munro (2012)	Recreationally active	2D	SLS Drop Jump SLL	FPPA	Within-day ICCs good reliability range .59 to .88, between-days ICCs good to excellent, range.72 to .91. SEM & SDD values range 2.72° to 3.01° and 7.54° to 8.93°	Eluded been proven before by other research no actual results to prove in this study
Munro (2017)	Football Basketball	2D	SLS SLL Drop Jump	FPPA	No	FPPA in the SLS was significantly correlated with SLL (r = .52, r2 = 27%) and DJ (r = .30, r2 = 9%), whereas FPPA in the SLL was also significantly correlated to DJ (r = .33, r2 = 11%). Discussion

2D – Two-dimension, 3D – Three Dimensional, FPPA – Frontal Plane Projection Angle, HADD – Hip Adduction Angle ICC- Intraclass Correlation, SLL – Single Leg Land, SLS – Single Leg Squat

The Tuck Jump Assessment (TJA) (Table 2.4)

The Tuck Jump Assessment (TJA) was initially reported within the literature (Knaus, 1993) approximately 10 years ago. Whilst anecdotally its use is widely reported by clinicians from both the sports science and clinical sectors, its prevalence within the literature is minimal with a literature search of 5 databases producing only 7 articles pertaining to the TJA. Initially designed as a field-based alternative to laboratory-based jumping and landing analysis, the test was devised to determine flaws in plyometric and neuromuscular components that were potential risk factors for mechanisms of ACL injury (Ford, Myer and Hewett, 2007; Stroube *et al.*, 2013; C. A. Smith *et al.*, 2017; Lininger *et al.*, 2017). It takes minutes to perform and requires minimal off the shelf equipment to capture subjects from frontal and sagittal views, making it a popular cost and space-saving test.

Unlike traditional drop jump tests, which usually only necessitate an athlete completing 1-2 jumps (Ekegren *et al.*, 2009; Padua *et al.*, 2009) the addition of a box is also required. Read *et al.*, (2016) have implied that the raised start position on a box involves muscles starting from a position of rest rather than propulsion which would typically be seen in a competitive environment where an athlete may have to run or cut before jumping and landing, and therefore some drop jumping tasks may artificially induce stabilising feed-forward mechanics that could obscure the capturing of an individual's instinctive movement pattern. The test requires the start and end from the floor and completion of repetitive jumps over a 10 second period, thus requiring a high-level effort that is representative of the landing techniques and fatigue levels that many athletes at all sporting levels encounter within their competitive environments.

Only four studies have analysed the reliability of the TJA (Knaus, 1993; Dudley *et al.*, 2013; Herrington, Myer and Munro, 2013; Fort-Vanmeerhaeghe *et al.*, 2017), with the focus on these studies being around rater reliability rather that within-subjects or the changes between sessional performance. Myer et al (2007) modified the original work to dichotomize the TJA to improve reliability reporting intra-rater reliability scores of ICC=0.84 (CI=0.72-0.97) (Chimera and Warren, 2016). Previous research (Herrington, Myer and Munro, 2013) completed by expert raters (ability level deduced as the second author conceived and developed the TJA) reported high inter-rater reliability utilising a percentage of exact agreement (PEA) reporting 93% PEA between the two testers (Range 88%-100%) and moderate to high kappa levels of 0.88 when scoring 10 university aged participants. Similar levels of high intra-rater reliability were also reported in male subjects (PEA 96-100%) and 87.2% for female subjects. It is possible that despite leaving a month between the review of trials, due to the expert level of both practitioners higher intra-rater reliability may have resulted, the applicability of these results to novice or inexperienced practitioners may not be generalised.

Conflicting evidence has been presented by Dudley *et al.*, (2013) who reported poor to moderate intra-rater reliability of 0.44 (95% CI 0.22-0.68) to 0.72 (95% CI 0.55-0.84) in 3 different levels of practitioners which included a 4-year post-graduate physical therapist, a 7-year post-graduate sports scientist and a 1st-year student physical therapist. Perversely the same authors also reported on inter-rater reliability of 5 raters (graded poor ICC= 0.47 95% CI 0.33-0.62) but failed to justify why all 5 raters were not included within the intra-rater analysis. The authors also utilised P-values to calculate significant differences between TJA scores, whilst they justify the improved levels of inter-rater reliability to learning effect of their raters between sessions, by failing to control for the type one errors amongst the multiple comparisons within their statistical methodology, may have affected result reliability.

Fort-Vanmeerhaeghe *et al.*, (2017) also expressed concern for the educational background and ability of raters to interpret and score TJA criteria, creating an argument for a modified version of the TJA that involved the changing of the original 0-1 dichotomous scoring system to an ordinal 0-2 modified scale. The authors also postulated that dichotomous scoring does not allow for the severity of movement dysfunction to be determined. Two raters of 5 years of experience were selected to compare volleyball players scores, with the authors reporting good to excellent intra-rater and inter-rater reliability (K = 0.65-0.91; PEA Inter-rater 92.1% range 91.7-95.8 %; ICC = 0.94, 95% CI = 0.88-0.97; PEA Intra-rater 90.8% range 83.3-100%).

This modified method has not been applied or critiqued elsewhere and is limited by the homogeneity of the sample. Despite the added additional ordinal criteria, only one rater used the 2-point modification on 1 item of the 10 areas scored, suggesting that dichotomous scoring is sufficient. No data was presented by this group of being able to use ordinal scoring as an injury risk severity score as previously mentioned in the hypothesis. Intra and Intertester reliability have started to be established, although it remains inconsistent, and additional work looking at its use within real-time and across different disciplines and levels of practitioners, as well as in multiple populations is worthy of further investigation to support consistent clinical use. Further research also needs to focus on the validity of this test which is yet to be established.

Between session-reliability has only been assessed within two papers (Read *et al.*, 2016; Fort-Vanmeerhaeghe *et al.*, 2017), however only (Read *et al.*, 2016) reported within-subject inter-session reliability for each of the assessed Tuck Jump criteria. 50 elite youth male football players were analysed using a test-retest design and determined via kappa coefficients that knee valgus was the only criterion to reach substantial agreement in both pre-peak height velocity (PHV) and post PHV groups.

The majority of the literature analysis female participants (Lininger *et al.*, 2017) which is potentially due to its links with the original formulation of the TJA being reported alongside ACL injury (Myer, Bates, *et al.*, 2015) and females being twice as likely to suffer ACL injuries than males (Hägglund, Waldén and Ekstrand, 2009; Powers, 2010; Chimera and Warren, 2016). There is a lack of literature in relation to male populations of all ages and females outside of a university cohort age range. Whilst the above studies suggest that TJA is reliable between raters, its reliability and validity as a movement quality tool within different age ranges, athletic abilities remain to be seen. The revisiting of the reliability and validity of the TJA to establish with subject variation across multiple populations is important to allow the scope of the TJA as a measurement quality tool to be fully understood. There have been no studies that look at other pathologies such as those found at the hip and ankle to see how TJA might be an indicator of the risk factors associated with these joints. Furthermore, no study has examined how longitudinal performance of the TJA to understand the variations in jump performance during a competitive season or training bloc, this is particularly important within a paediatric population where changes in performance due to maturation and growth may be identified

Table: 2.4 Summary of studies analysing Tuck Jump Assessment

Study	Sport	Method of Analysis	Functional Test/Test Battery	Movement Quality Outcomes	Reliability Reported	Validity Reported
Dudley, (2013)	Recreationally active college students	2D	TJA	All TJA movements	Intra-Rater & Inter-rater. Inter-rater Poor ICCs 0.47; 95% confidence intervals (CI) 0.33–0.62. Intra Rater poor to moderate, ranging from 0.44 (95% CI 0.22–0.68) to 0.72 (95% CI 0.55–0.84	No
Fort-Vanmeerhaeghe (2017)	Volleyball	2D	TJA	All TJA movements	Intra- and inter-rater k was good to excellent for most items (0.65-0.91) % of exact agreement 83.3 to 100% in all scored items	No
Herrington (2013)	University level no specified sport	2D	TJA	All TJA movements	Kappa Values intra-inter tester reported only	No
Lininger (2015)	University level no specified sport	2D	TJA	All TJA movements	Exploratory factor analysis on common technique flaws. Fatigue, distal landing pattern, proximal control account for 46% of TJA variance within cohort	No
McCunn (2017)	Recreationally active college students	2D	Anterior Reach SL Deadlift Tuck Jump In-Line Lunge SL Hop for distance	SIMS	Weighted kappa values moderate within and between rater values (0.43-0.60) Within-occasion values k was 0.73 All values on composite scoring of TJA	No
Smith (2016)	University level no specified sport	2D	TJA	All TJA movements	p-values	No

2D – Two dimensional, ICC – Intraclass coefficients, SIMS – Soccer Injury Movement Screen, SL – Single Leg, TJA – Tuck Jump Assessment

2.4.5 Summary

The analysis and monitoring of human movement appear to contribute to the identification of risk factors associated with sporting related injury rather than the predication of injury itself. This current section of the review suggests that the exploration between movement assessment tools, tasks and links to injury risk has presented mixed results. Whilst 3D motion analysis is considered the gold standard for methodological process, the limitations of its practical application outside the laboratory setting are well documented. There is general consensus that future research directions for human movement are headed towards the field-base. Due to its portability, time, cost and practitioner training effectiveness, 2D video analysis have been offered as the likely resolution to the 3D limitations, with varying research successfully showing correlations and relationships between 3D and 2D kinematic variables. However, 2D as a stand-alone method is limited in its ability to capture complex multi-planar motions.

A small number of studies have undertaken qualitative visual assessment via observational tasks, however criticism remains around its subjectively and widespread use. Overall it appears that no movement assessment tool or task is without fault. Qualitative assessment shares the advantageous aspects of 2D methods, whilst also offering additional options around the capture of complex movement in a descriptive way that is different to 3D assessment. Limited studies have attempted to validate human visual assessment to 2D methods and whilst it appears logical that an individual's movement quality would have meaningful, impactful implications on injury risk, further research to evidence theses conjectures is required. Despite the limitations of movement assessment reported in the literature, qualitative methods seem to provide a viable approach to assessment and tracking of movement and its changes in its entirety. As overall movement quality as assessed by 2D and 3D methods still appears to be reported in isolated measures (see movement quality in section 2.4).

When taken into context of the implications discussed in sections 2.2 and 2.3 of the review, regarding the sequence of development of injury prevention rationale, models and frameworks and the efficacy of prevention strategies. Due to the highly complex, multifaceted and unique nature of human movement, human movement is likely to make up a small component of the complex collective that comprises sports injury.   It is therefore potentially unrealistic to find incredibly strong relationships between movement quality and definitive injury risk. However, as one of the most modifiable factors of injury risk and risk mitigation, human movement appears to remain an essential factor for practitioners wishing to address profiling tools and prospective injury risk. Additional investigation into 2D analysis and the qualitative method is required, to better meet current complex systems approaches of injury prevention frameworks, by providing continual feedback in a contextual way. This may provide practitioners with valuable information on the performance of the individual, as well as addressing knowledge gaps between physical quality performance measures and injury risk and therefore the role of qualitative analysis needs to be further explored.

Following completion of the methodological chapter, it was clear that further investigation into a youth population was required. Due to the unique requirements of this particular population, additional searches were made of the literature to better inform the methodology and future potential applications. This is presented in the next section of the review.

2.5 Relationships between movement quality and injury risk in the youth athlete

Participation in sport during childhood and the teenage years is a primal cause of overuse and acute msk injuries, with continual repetitive actions, longer training times and exposure being cited as the main cause for placing the bodily structures under risk and leaving this group susceptible to injury. These injuries themselves can counteract the positive benefits associated with sports if youth are no longer able to partake following injury (Rejeb *et al.*, 2017).

2.5.1 Operational definitions

Within the youth sports science literature terms and definition referring to growth and maturation are frequently used interchangeably and synonymously. Despite each individual term referring to specific biological processes, direct comparison between literature can be complicated and confusing (Malina, 2014). For simplicity for this review, growth refers to the changes in the size of the body and the individual anatomical segments (Malina, 2014).

Maturation refers to the process of biological maturity (Cumming *et al.*, 2017) and is considered in terms of tempo, timing and state. Each maturational state, timing and tempo occurs at a variable and independent rate among individuals (Difiori *et al.*, 2014; Malina, 2014; Cumming *et al.*, 2017), while growth and maturation are a continually evolving state, maturity itself is an end state (Malina, 2014). Pre-adolescence refers to participants who have not started adolescence (Myer *et al.*, 2011). In chronological terms adolescence frequently incorporates participants between the ages of 10-18, but has been shown to span the period of 9-26 years (Curtis, 2015). Due to the aforementioned variation in maturity timing and rates, adolescence in itself is a continually evolving construct and the concept remains difficult to clearly define (Quatman-Yates *et al.*, 2012; Difiori *et al.*, 2014; Cumming *et al.*, 2017), the most concise definition is that of the time between pre-adolescence and adult hood (Malina, 2014).

2.5.2 Determining growth and maturation

Biological maturation is considered to be a confounding factor on the development of physical qualities and performance capabilities of the adolescent athlete (Towlson *et al.*, 2018), although small in number and predominantly conducted in football several studies (Vaeyens *et al.*, 2006; Read *et al.*, 2018) have attempted to identify the interactions between biological maturity and development of performance characteristics. The accuracy of methods adopted by practitioners to measure maturity, and how these maturity estimates may influence profiling and the assessment of movement quality impacting injury risk remains indistinct (Malina *et al.*, 2015; Towlson *et al.*, 2018, 2020).

Whilst biological maturity is asynchronous between individuals, the process can be described via state (the biological state at the time of assessment or intervention), tempo (rate of which maturation occurs) and timing (the timing of maturation relative to chronological age) (Cumming *et al.*, 2017; Towlson *et al.*, 2018). Biological maturity can be measured via a range of different methods from radiograph assessment of skeletal age, the development of secondary sex characteristics (often through a tanner scale), and endocrine evaluation of hormonal changes (Malina *et al.*, 2015; Kozieł and Malina, 2018). Traditionally, the most accurate methods for determining adult height and maturity are skeletal-age and establishment of secondary sex characteristics (Malina *et al.*, 2015). These methods are typically expensive, require specialist input and are frequently considered invasive and impractical (Kozieł and Malina, 2018). Subsequently, in more recent years several non-invasive somatic methods have been developed and are more widely used within sports medicine literature, with maturity offset the most common selected to evaluate maturity (Malina *et al.*, 2015). Both the Mirwald *et al.*, (2002) and Khamis and Roche, (1994) methods are feasible, non-invasive alternative methods that use predictive equations to estimate adult stature (Myer *et al.*, 2011). Maturity off-set utilises height, seated height, body mass and chronological age via sex-specific equations to forecast peak height velocity (PHV) (Mirwald *et al.*, 2002). Although non-invasive and practically feasible, maturity off-set has limited proven validity beyond on-time maturers, with its accuracy in early and late maturers questionable (Malina *et al.*, 2015; Kozieł and Malina, 2018). This could be potentially problematic, as due to the perceived gains in physical qualities and performance associated with early maturation (Cumming *et al.*, 2017; Mann and van Ginneken, 2017; Towlson *et al.*, 2020), a large number of adolescent athletes would classify as early maturers, with application of these methods possibly resulting in over or underestimated prediction.

The Khamis-Roche method also selects the anthropometric measures of height, body mass and chronological age in conjunction with biological parental height to estimate mature-stature (Khamis and Roche, 1994; Towlson *et al.*, 2020), with estimations of maturity status then being able to be presented as a percentage of predicted adult height (known as bio-banding) (Malina *et al.*, 2015; Cumming *et al.*, 2017; Towlson *et al.*, 2020). Timing of maturation comparative to sex and age specific standards can also be reported via z-scores to define delayed or advanced maturation in adults (Towlson *et al.*, 2020).

Although the data from either equational method is intrinsically valuable to practitioners, limitations that could incorrectly categorise a participants maturation status do exist (Towlson *et al.*, 2018).Limitations of the non-invasive predication equations include measurement errors of $\pm$ 1 year (Lloyd *et al.*, 2015; Kozieł and Malina, 2018) for maturity off-set, and around a median error of 2xm for the Khamis-Roche method (Towlson *et al.*, 2020). It is important to note that both the invasive and non-invasive approaches to determining growth and maturation have underlying limitations and assumptions, and to date no-single method can be claimed as a gold-standard (Malina *et al.*, 2015; Kozieł and Malina, 2018), however the importance of contextualising growth and maturation encountered during adolescence to further advance the field of profiling to improve understanding of injury risk remains paramount. The field of maturation and growth measurement is still emerging and continually evolving, as such further analysis and critique of the various methods is beyond the scope of this current review. What is clear from the literature, is the growing potential importance of maturational status within movement assessment of the youth athlete. Whilst the limitations of the non-invasive methods are acknowledged, inclusion of maturational measurement is now forming best-practise when considering the adolescent athlete, to date prediction equations appear to have the greatest utility as none-invasive, reliable, affordable and time-appropriate measurement tools to deliver this.

2.5.3 Frequencies and causes of injury in the youth athlete

Substantial financial and resource investment into talent identification and development systems has occurred in recent times, with some youth athletes finding themselves in receipt of similar levels of sports science services that would rival an adult setting (Rongen *et al.*, 2018). The "professionalisation" of the youth sport system has spawned an entire industry quite quickly, and whilst the caveat of how you truly define professionalism at the youth level remains (Swann, Moran and Piggott, 2015) there is greater emphasis placed on competition and success from ever earlier stages of childhood (Von Rosen et al., 2018). Comparative to their adult counterparts, injury epidemiology within the elite and amateur youth level is less frequently reported (Rejeb *et al.*, 2017), only 2 studies have been found that have examined incidence and pattern of injury across youth multi-sport athletes. Reported injury incidence in adolescent athletes varies between 4.1-5.5% per 1000 hours of training and competition (Rejeb et al., 2017; Von Rosen et al., 2018), comparative to the 6.3% per 1000 hours observed in university-aged equivalents (Yang *et al.*, 2012), the results of which suggesting that there is an increase in injuries with each consecutive sporting season.

In their study on 166 multisport male athletes, age 12-18 years Rejeb *et al.*, (2017) reported that 67% of injuries affected the lower limb, with 50.3% sustained from overuse and around 20% attributed to growth. Von Rosen, Heijne, *et al.*, (2018) demonstrated similar results in 284 adolescent athletes (although his study selected a mixed-gender cohort) with 69% of reported injuries affecting the lower limb, whilst these authors did not divide injuries into overuse or growth-related, alarmingly they did report that 22% of injuries resulted in total absence from normal training for 2 or more months, with some athletes in certain sports demonstrating higher injury rates than adults. Paterno *et al.*, (2010) stated that the majority of adolescent related sports injuries occurred due to trauma, but estimated that 30-50% of sporting injuries and had overuse mechanism.

During adolescence, abundant physiological changes rapidly occur due to maturation and growth phases with many experts suggesting the process of growth being a primal cause of injury within the youth population (Rexen *et al.*, 2016). Muscular strength, force production, motor skill mastery develops at a heightened rate during adolescence, however, there is now increased concerns that adolescents and children are now presenting with insufficient levels of motor skill and potential sub-optimal motor patterning (Ford, Myer and Hewett, 2010). During adolescent growth spurts, the rapid changes in mass, stature, strategies for controlling movement and adoption of modified movement are thought to be associated with heightened injury risk (Atkins *et al.*, 2016; Read *et al.*, 2018). However, it remains unclear if the growth spurt solely contributes to injury risk, or if it is the cumulative effect of multiple ranges of factors such as training load, size, maturity, psychosocial development, behavioural change (Curtis, 2015; Cumming *et al.*, 2017).

Similar to the complex systems approaches suggested in current injury prevention frameworks, it appears that further research into the relationships and interactions between multiple factors within the adolescent population is required to further understand the contribution, if any, of growth and maturation to injury causation. Children and adolescents may change their performance as they mature, gain strength or just become better at the tasks of jumping and landing. Therefore, analysing and quantifying the effects of maturation and growth on landing kinematics may help professionals identifying normative movement patterns and age-associated changes in lower limb kinematics (both positive and negative). Overall, despite a greater awareness of the frequencies and causes of injury within the youth athletic population, due to the multifactorial causes of injury a great many factors pertaining to injury risk and effective strategies for prevention within this group remain unknown (Stracciolini, Sugimoto and Howell, 2017).

2.5.4 Risk factors in the youth athlete

As with the adult literature, injury risk within an adolescent youth population, appears to be multifactorial (Difiori *et al.*, 2014; Stracciolini, Sugimoto and Howell, 2017). A variety of both intrinsic and extrinsic risk factors have been implicated in the adolescent literature. Whilst the majority of the research is focused around football (Fort-Vanmeerhaeghe *et al.*, 2016; Read *et al.*, 2016, 2018; Hughes *et al.*, 2018), the most commonly researched risk factors are chronological age, gender, fatigue, history of previous injury, biomechanical factors, workload, sports equipment and fixture congestion (Difiori *et al.*, 2014; Fort-Vanmeerhaeghe *et al.*, 2016; Rejeb *et al.*, 2017; Stracciolini, Sugimoto and Howell, 2017; Von Rosen, Heijne, *et al.*, 2018). Adolescent awkwardness, is a commonly used but poorly defined term that refers to changes in motor performance (notably neuromuscular and postural control) encountered during growth (Quatman-Yates *et al.*, 2012; Difiori *et al.*, 2014; Towlson *et al.*, 2020). Disrupted motor skill is widely anecdotally reported in youth, although research pertaining to its identification, classification and measurement both cross-sectionally and longitudinally is scarce (Quatman-Yates *et al.*, 2012). Resultantly the cause of adolescent awkwardness remains unclear, there appears to be links to the alterations in sensorimotor mechanisms encountered during rapid growth (Quatman-Yates *et al.*, 2012; Difiori *et al.*, 2014). Further investigation and understanding regarding these changing movement strategies detected during growth, is important to practitioners to enhance not only profiling and monitoring, but to begin to unravel if adolescent awkwardness related NMC changes are an injury risk factor in the adolescent athlete. With movement patterns being considered the most modifiable risk factor in an adolescent population, although limited in their number, NMC intervention studies seem to have been the primal focus of the motor performance profiling literature.

Research by Fort-Vanmeerhaeghe *et al.*, (2016) identified around fourteen different injury risk factors specifically linked to NMC causes within an active youth population. Whilst the review provided information on proposed training focus to mitigate the identified risk, they were unable to provide further information regarding the relationship between the specific elements of NMC and subsequent injury occurrence. This is supported in later prospective work by Von Rosen *et al.*, (2017). One of the largest prospective studies specifically on adolescent risk factors in sport, whilst Von Rosen *et al.*, (2017) identified many risk factors throughout the literature they appeared inconsistent and predominantly associated with adult, not adolescent athletes. The predominant findings of the study, was the combination of a decrease in sleep volume with an increase in training load and intensity, comparative to no change in those variables, with elevated injury risk.

Whilst the paper has provided important background information supporting the complex systems approach by evidencing the result of injury occurrence through the complex interaction of multiple factors of risk. The age range of the 732 participants was 15-19. It is highly possible that a large proportion of the cohort had undergone their growth spurt or even completed their maturational process, and therefore the applicability of the identified risk factors for participants at different stages of the growth and maturational process remains unknown.

When considering biomechanical investigation of NMC within this age group, similar to the adult literature, studies are frequently limited to the reporting of isolated kinematic variables, with the majority of studies investigating dynamic knee valgus, usually during a single leg squat (Bell *et al.*, 2013; Horan *et al.*, 2014; Comfort, Colclough and Herrington, 2016; Holden *et al.*, 2017; Stracciolini, Sugimoto and Howell, 2017). Holden *et al.*, (2017) assessed the use of FPPA on 2D and 3D measurements during a drop landing in seventy-six adolescent females to determine if FPPA could predict the risk of PFP. It was demonstrated that those participants who went onto develop PFP had presented with significantly more knee valgus displacement (mean difference = 7.79°,p = 0.002) compared to those who had not. Classification of participants was done via chronological age, rather than biological maturational status, and therefore the understanding of FPPA as a factor of injury risk or as a movement pattern of growth, remains unclear. Curiously, whilst chronological age is commonly reported, very few studies (Read *et al.*, 2016; Agresta *et al.*, 2017; Räisänen *et al.*, 2018; Ellenberger *et al.*, 2020), consider maturational status alongside neuromuscular assessment of biomechanical factors. There is a general paucity of research that explores neuromuscular elements of proposed risk factors throughout the growth and maturation process, and subsequent work is required, to further understanding of the relationship between profiling, the adolescent movement changes encountered during growth and injury risk.

Peak Height Velocity (PHV)

Peak height velocity (PHV) is the time where maximal rate of growth occurs and is typically established via an equational method (Read *et al.*, 2018), usually occurring around the age of 12 in females and 14 in boys, however, can vary between the ages of 10-16, traditionally growth spurts start earlier and are of shorter duration in females. Therefore there are large variations as those that have the same chronological age may not demonstrate the same biological age (Mills *et al.*, 2017). Frequently during this time, there is a disparity between strength and flexibility, and a disconnect between skeletal and muscular development where long-bone and trunk length develops prior to muscles attaining full strength and size (Van der Sluis *et al.*, 2015).

These changes are typically associated with overuse injuries such as Osgood-Schlatter's where the increased stress on ligaments, growth plates, apophyses and muscular-tendinous junctions is thought to result in a temporary inability of bony tissue to deal with the capacity of this load. Similarly, the increase in traumatic injuries, such as acute fractures during this period of growth are thought to be attributed to interim variation in bone density and variable changes in joint stiffness (Wild, Munro and Steele, 2015; Hopper *et al.*, 2017; Palmer *et al.*, 2018). A limitation of PHV as a method of determining growth is that conclusions can only be made retrospectively, however its use is clinically important to guide the timing of individuals loads and exposure for the developing athlete. The changes within these systems seen during PHV may attribute to abnormal movement patterns and a decline in quality kinematics which may contribute to the reported increase in injury incidence in the youth population. The definitive process of the growth spurt as an independent risk factor itself, remains unclear.

2.5.5 Influence of Sex and Gender

In earlier research neuromuscular patterns of movement during assessment tasks have been shown to deviate between boys and girls during the maturational process (Hewett *et al.*, 2005). Compared to their male counterpart's female youth athletes demonstrate decreased levels of power, strength and indexes of performance (Hopper et al., 2017), these changes in growth patterns can have significant differences in physical preparation and performance. Due to rapid changes in musculoskeletal structure, such as limb length and height, increase in knee joint laxity and developmental lag in quadriceps and hamstring strength – females are thought to be at greater risk of ACL injury post-puberty (Wild, Munro and Steele, 2015). Research by Ford, Myer and Hewett, (2010) demonstrated an increase in ankle stiffness, peak ankle dorsiflexion moments but no change in ankle dorsiflexion in youth females throughout growth spurt period during vertical drop landings, whilst longitudinal in design, participants were only tested annually during two-year period and it remains unclear if this is frequent enough to capture kinematic changes during growth spurts. In a descriptive laboratory study on 33 healthy females (age 10-13) Wild, Munro and Steele, (2015) reported that throughout their growth spurts girls exhibited reduced knee flexion and hip adduction moments, and increased hip flexion and external knee abduction moments during horizontal landings.

Whilst the research focus appears to have been placed on female athletes (potentially due to the proposed ACL injury risks), males have also been shown to demonstrate aberrant landing mechanics during periods of growth. Male football players have shown to demonstrate higher dynamic knee valgus (DKV) during a jump assessment task with deviation in landing mechanics becoming more pronounced in those aged 13-15. Poor neuromuscular control has been demonstrated to influence lower limb landing in both youth and adult athletes (Weinhandl, Irmischer and Sievert, 2015; Burnham *et al.*, 2016; Ithurburn *et al.*, 2017), following maturation females display deficits in neuromuscular control (Comfort, Colclough and Herrington, 2016; Hopper *et al.*, 2017), which may be pertinent to the development of poor movement patterns and disparity in injury rates between male counterparts.

More recently, other researchers have reported no significant differences in knee position, or compound scoring during single-leg squats or drop landings (Ugalde *et al.*, 2015; Agresta *et al.*, 2017; Räisänen *et al.*, 2018; Ellenberger *et al.*, 2020) between gender group. Although differences in FPPA angles between girls and boys were expressed in two papers (Räisänen *et al.*, 2018; Ellenberger *et al.*, 2020) all differences were statistically non-significant. Interestingly, within the same research papers, maturational status related differences in movement quality assessment has been demonstrated for both genders (Agresta *et al.*, 2017; Räisänen *et al.*, 2018; Ellenberger *et al.*, 2020). There appears to be conflicting literature regarding gender related differences in movement quality. During adolescence and through the growth process, biological sex-related differences are evident (Parsons, Coen and Bekker, 2021), this is in addition to the potential influence of the adult literature, where women's injury risk has largely been reduced to hormonal, anatomical or physiological biological causes (Nimphius, 2019; Fox *et al.*, 2020). The concept of sex-specific gender related movement quality differences within the adolescent athlete is highly pervasive and could in its be a confounding factor, as also evidenced by the non-significant gender effects noted in the above papers (Agresta *et al.*, 2017, Räisänen *et al.*, 2018; Ellenberger *et al.*, 2020).

When this concept is further overlaid with the complex systems approach presented by Bittencourt *et al.*, (2016), the consideration of the adolescent in a wider environmental context beyond gender related differences is likely to be more impactful on understanding risk factor interactions and the required interventions for those pursuing youth sport (Nimphius, 2019; Fox *et al.*, 2020; Parsons, Coen and Bekker, 2021). Peak height velocity (PHV) occurs between 85-96% of predicted adult height (PHV), and the most predominantly at 90-92% PAH (Cumming *et al.*, 2017), adolescent growth spurt patterns therefore appear to be the same regardless of gender. Accordingly, future research investigating movement assessment and subsequent injury risk in the youth athlete, should incorporate measures of growth and maturation in adolescent athletes of both genders.

2.5.6 Movement quality assessment in the youth athlete

As with adult participants, the rational for assessing movement quality within the youth population involves identification of athletes who demonstrate movement patterns associated with injury risk, the use of appropriate profiling methods and an intervention usually targeted at NMC deficits (Read *et al.*, 2018). Poor NMC is believed to attribute to poor movement patterns that predispose youth athletes to injury, and changes in NMC are therefore considered a primal risk factor for increased of youth athletic injury (Whatman, Hume and Hing, 2013; Read *et al.*, 2016). Movement profiling tools are commonly used to assess and quantify movement quality to try to identify deficits that identify injury risks, and as such numerous tests of functional performance have been developed (C. A. Smith *et al.*, 2017).

Similar to the adult population, movement quality in the youth athletes appears to be assessed as part of a movement battery (i.e. the FMS) via different tools or tasks. Or via singular movement tasks (i.e. squat, drop landing, tuck jump) where composite scores of the task are provided, or isolated kinematic or kinetic parameters of a particular joint (i.e. dynamic knee valgus at the knee) are reported.

Singular Tasks

Commonly reported movement assessment tasks used within the available adolescent literature are the single leg squat and a vertical drop jump. The tasks appear to be popular due to the ease of use, replication of common sporting movements, and association with proven reliability and validity to lower limb injury risk factors, such as increased hip and knee movements and DVK (Ford, Myer and Hewett, 2007; Whatman, Hume and Hing, 2013; Raïsänen *et al.*, 2016; Read *et al.*, 2016; Agresta *et al.*, 2017; A M Räisänen *et al.*, 2018).

The single leg squat is a highly utalised task in clinical practise as it is replicative of daily tasks, sporting movements that require trunk control over a planted leg, and is frequently symptom provoking (Raïsänen *et al.*, 2016). The unilateral movement has been analysed in youth athletes via 3D measures (Ford, Myer and Hewett, 2007; Whatman, Hume and Hing, 2013; Horan *et al.*, 2014), 2D motion capture (Raïsänen *et al.*, 2016; Räisänen *et al.*, 2018; Ellenberger *et al.*, 2020) and via visual rating criteria (Agresta *et al.*, 2017). The majority of authors have evaluated FPPA angle, or a dynamic knee valgus, with several authors trying to identify relationships of kinematic and kinetic parameters to performance.

Raïsänen *et al.*, (2016) investigated the intra and inter-rater reliability of the single-leg squat test by 2D FPPA and physiotherapist visual assessment in 378 athletes age 14-22 years of age. The results demonstrated fair to very good (κ =0.28-0.89) intra-rater reliability, and poor to fair (κ=0.16-0.32) inter-rater reliability between an experienced and non-experienced rater. Whilst the study highlighted the requirement to improve rater-training, good correlations (κ =0.63-0.64) between the 2D FPPA measures and subjective assessment, highlight the potential further use of observational methods by practitioners in a youth cohort.

Associations between different methods of knee measurement were also moderate to very large (r=0.39-0.87) in a study by Whatman, Hume and Hing, (2013) showing good correlations between peak knee kinematics in 10-12 year old athletes between dual and single limb tasks. They used both 2D and 3D methods to calculate knee joint angles, although the cluster marker sets used are described it remains unclear if the same or different markers were used for both 2D and 3D evaluation of medial knee displacement. The authors also assessed within (ICC=0.60-0.92) and between-day (ICC 0.26-0.84) reliability demonstrating moderate to high reliability of the 2D-3D methods, but potentially large performance variability of the task by participants. Whilst Whatman, Hume and Hing, (2013) provided typical error scores for within and between day kinematic measurements, neither they or Raïsänen *et al.*, (2016) provided information regarding SDD or SEM of measurement scores. Therefore, gaining an understanding of what is required for true performance changes in the youth population remains difficult.

Horan *et al.*, (2014) also investigated the relationships between 2D and 3D measures and visual methods of single-leg squat performance to try to differentiate between poor and good squat performance in young adults. Kinematic parameters of the pelvis, hip, knee and ankle revealed that SLS that were classified as poor in performance via visual rating criteria where characterised by greater hip adduction, less knee flexion and greater knee valgus than those classified as good. As Horan *et al.*, (2014) observed their participants from the frontal and sagittal views results suggest that 2D and visual assessment is valuable beyond the frontal plane.

Räisänen *et al.*, (2018) attempted to further their FPPA work in a later paper by trying to establish a relationship between FPPA in 11-14-year-old footballers and sustaining an acute lower limb injury. No links between FPPA and injury were demonstrated in the mixed gender cohort, however presence of FPPA during a single-leg squat appeared to improve with age with older boys displaying smaller angles. FPPA was concluded not to be a risk factor for lower limb injury in younger children with the research group concluding that children under 13 are at lower risk of acute lower limb injury. Regardless of the large sample size, the study presented participants by chronological age. Chronological age has been shown not to be a good indicator on which to base movement performance and injury risk. As movement, behaviour, cognitive and motor skills develop and regress at different times and rates, regardless of chronological age (Difiori *et al.*, 2014). It is possible this impacted the level of significant associations between age, gender, leg dominance and injury risk. It therefore appears difficult to fully discount risk factors of injury by chronological ages. This concept is further supported in research on youth and elite alpine skiers where biological maturation, not chronological age or gender, was found to be the confounding factor in knee valgus screening via 3D methods (Ellenberger *et al.*, 2020) during drop jump and SLS.

Other authors have assessed single-leg patterns within an adolescent population during landing in football players (Read *et al.*, 2018), asymptomatic active children and a control group (Estevan *et al.*, 2020) and youth and young adult ACLR participants (Ithurburn *et al.*, 2017). Read *et al.*, (2018) found that kinetic and kinematic measures (jump height, peak vertical ground reaction force (pVGRF), FPPA and trunk side flexion) collected in youth academy footballers, showed changes in measures when analysed by different maturational stages. During single-leg countermovement jumps there were linear increases in vertical jump height and pVGRF ($p<0.001$; $d=0.85$-2.35) at pre, circa and post PHV stages of maturation. Kinematic variables also demonstrated trends in reduced DKV and larger trunk flexion with developing maturation. Further highlighting the variation of movement quality during differing stages of maturity, and the importance of consideration of phase, stage, time and tempo during movement assessment within this population group.

Qualitative assessment of movement quality in the youth athlete and young adult is less prevalent within the literature, but has been assesses in the bilateral condition via the tuck jump assessment and the landing error scoring system (Padua *et al.*, 2015; Read *et al.*, 2016; Fort-Vanmeerhaeghe *et al.*, 2017).

Both Read *et al.*, (2016) and Fort-Vanmeerhaeghe *et al.*, (2017) assessed the reliability of the TJA in adolescent populations each author considered different sides of the same coin, with Fort-Vanmeerhaeghe *et al.*, (2017) assessing rater reliability and Read *et al.*, (2016) determining intra-rater reliability of the method and within-participant variation in a pre and post-PHV cohort. Excellent inter-rater agreement (ICC=0.94, 95% CI .88-.97) and overall excellent intra-rater agreement (ICC = 0.94, 95%CI .88-.98), across all qualitative TJA criteria has been demonstrated (Fort-Vanmeerhaeghe *et al.*, 2017). Read *et al.*, (2016) was able to identify within-subject variance of TJA, with strong intra-rater reliability (ICC = 0.88). Although demonstrated in young adults (18-23 years) similar levels of inter-rater reliability (ICC= 0.72-0.81) have also been demonstrated in the LESS (Padua *et al.*, 2011, 2015). Only Read *et al.*, (2016) gave consideration to stage of growth, given the potential links of maturational performance differences during movement assessment (Malina, 2014; Cumming *et al.*, 2017) further consideration of growth and maturation within qualitative assessment might be beneficial. Although each of the studies established the potential use of qualitative methods of movement quality assessment in the youth athletic population, methods are limited to bilateral landing tasks. As unilateral tasks are more likely to demonstrate patterns of movement more relative to the sporting environment, it seems pertinent to consider qualitative assessment of single-leg tasks within this population.

Surprisingly, to date only one paper (Agresta *et al.*, 2017) appears to have evaluated a unilateral movement pattern within the adolescent population, considering both qualitative assessment and maturational influences. The author used non-invasive methods to determine PHV (Mirwald *et al.*, 2002), interestingly maturity status did not significantly influence a qualitative compound criteria of SLS scores, but chronological age did. Further post-hoc analysis of the individual criteria suggested certain components of the scoring where synonymous and significantly associated with maturation phase. This study findings provide further evidence for varied and interchangeable maturational rates of body segments, but also the highly individualist nature of movement of an individual. This highlights the complexity, but also the potential of qualitative utility for an adolescent cohort, as long as maturity and composite and component scores are presented.

Movement Batteries

Currently, despite the growing interest in movement test batteries within youth development programmes, there is generally less available literature within the adolescent population. The limitation of utility of movement screening and movement profiling for injury prediction in the adult literature, may have dissuaded additional research in adolescent cohorts. However, there is current evidence to suggest that movement assessment tools such as the FMS, netball movement screening tool (NMST) and governing body devised tools (such as FIFA 11+) may have a relationship to performance measures in adolescent athletes.

Lloyd *et al.*, (2015) explored relationships between FMS, measures of maturation against reactive agility and RSI in male football players age 11-16. Results revealed significantly moderate to strong (r = 0.4-0.7) relationships of FMS components to some or all of the performance measures. Similar to Lloyd *et al.*, (2015), Parsonage *et al.*, (2014) gathered reference data for conditioning specific movement tasks and physical fitness characteristics in under 16 rugby union players. Relationships were demonstrated between players with reduced movement screening scores and subsequent slower performance of physical quality tests of sprint time, yo-yo tests and reduced vertical jump heights. Although limited to male footballers, the importance of considering the context of maturation when evaluating movement quality has also been demonstrated Portas *et al.*, (2016). Whilst the FMS itself is not a particularly strong measurement tool regarding transfer of performance of the selected movements within FMS to athletic performance or injury risk, the stability of the FMS test was substantially impacted by the participants status of maturity. Significant negative correlations between improved movement assessment scores, decreased sprint times and 505 change of direction times (r= >0.4, p = < 0.05) have also been found in adolescent females (Hopper *et al.*, 2017). Collectively, studies appear to suggest movement quality assessment could be related to athletic performance in youth populations, rather than identification of injury risk. A conflicting study (C. A. Smith *et al.*, 2017) has reported significant differences in functional performance tests battery scores between uninjured and injured groups.

Smith *et al.*, (2017) prospectively investigated and combined composite scores of SEBT, drop jump, hops and fitness tests in 101 12-16-year-old athletes from several different team sports. Following a seasonal long surveillance period (although exact times were not documented), composite test scores were found to be significantly different in injured and uninjured male and female (p = .016, p - .008) respectively. With the greatest differences demonstrated in drop jumps and double-leg lower tasks. Whilst results suggest the further potential use of movement assessment tasks as identification of injury risk factors, the lack of investigated and reported exposure data during the surveillance period of the study warrants further caution around identification. All papers were generally limited by small sample sizes, and cross-sectional approaches, that indicate the additional investigation of longitudinal work to fully understand the potential benefits of movement assessment in the youth population, to track and monitor measurements of performance.

2.5.7 Summary

Some key concepts around adult profiling frameworks and injury prevention strategies appear relevant in the adolescent arena. However, adolescent athletes are not miniature adults. Associations, relationships and correlations, should be considered in the context of the developing body. With acknowledgement and accommodation of the normative factors of growth from biological to behavioural. Practitioners maybe required to adapt injury prevention models and strategies, and the assessment of movement quality and injury risk factors, not only for interindividual variations of movement, but also for maturational influence on movement. Despite the lack of available evidence to report on the effects of growth and maturation on specific musculoskeletal screening tools, this small body of research demonstrates that through periods of growth during adolescence, girls and boys demonstrated differences in the lower limb strategies they employ during landing and that any changes in strategy observed kinematically maybe considered a risk factor in the development of overuse or traumatic injury. The development of affordable and accessible field-based movement assessment tools and tests are required to determine movement capability and potentially changing movement patterns observed during growth and maturity. Longitudinal studies that follow movement pattern performance with childhood and adolescence kinematics are lacking, and an understanding of how movement patterns evolve during the growth process (not just chronological age but maturational status) are important to further understanding of injury susceptibility and readiness to return to training within the adolescent group.

2.6 Literature review conclusion and rationale for research

In recent years the underpinning philosophies regarding MSK profiling and screening have been called into question. The review of the literature has highlighted the juxtaposition between current rationales for injury prevention, understanding of the injury problem beyond a medical model and the effectiveness of injury prevention strategies. The evolution of injury prevention models and frameworks is changing the narrative regarding the complexity of injury phenomena, to embrace the multifactorial web of determinants that influence injury in a dynamic and burgeoning way. The expanding literature and knowledge base regarding injury prevention rationale and current concepts of evaluating the broad range of contextual variables that impact injury, appear to have demonstrated "why" injury profiling should evolve. However, the "how" behind the approach of the instigation of profiling still appears to be inappropriate to the complex paradigm presented by the injury problem. The reductionist perspective of the biomedical process remains cardinal primarily due to the cause and effect and simplicity to decision making propagated into the literature and clinical practitioner approach.

There is a need to move beyond the current concepts of injury and profiling as attained from the knowledge of previously reductionist theories, models and methodologies. If injury burden is explored away from the linear concept of prediction, inference and intervention, and is considered within the context of how it impacts the injury problem. Then injury burden can be viewed more holistically as an outcome of the wider problem, where the wider problem of sports injury is the general inability of the sports medicine community to fully evaluate the complex drivers of the injury problem, its risks and interventions. Within the youth athlete, growth and maturation appears to be one of the drivers of complexity, which poses new questions around the reconsideration of profiling generally from a different frame, and also that of "how" and "why" it may be applied within a complex population such as adolescence, which will further build on the consideration of applied context.

In the pursuit around the identification and monitoring of risk factors, for prospective injury risk, 2D and qualitative assessment demonstrate the potential to be successfully investigated as MSK profiling tools. It was evident from the review that injury remains a significant problem in adult and adolescent populations across all levels of participation. Given the potential impact on individual and health care systems the continuation of mitigating the impact of injury severity and occurrence remains paramount. Gaining further understanding how viable, practitioner-friendly methods of movement assessment potentially fit with injury risk is warranted. It appears that there are gaps in the injury risk reduction literature between laboratory set gold-standards and practical application which is limiting universal understanding of the effectiveness of injury prevention interventions. When reviewing the latest injury prevention models and frameworks, evidence exists to support the complex systems approach, not only to injury risk reduction but to human movement analysis and preventative interventions. This will further allow practitioners better understanding of context that will reduce the research gaps between clinical utility evidence and real-world implications.

Injury remains a complex multifactorial issue within both the adult and adolescent populations. Intricate interactions of multiple factors around risk causation, methodological design and assessment remain. It is likely that no single-factor is likely to provide adequate explanations or preventions of injury. Therefore, MSK profiling tools that can work with the inherent variability of human movement, keep up with the rate of change to provide better insight into sports injury, are required to better guide future profiling and reduce injury risk.

2.7 Thesis aims and objectives

The current objectives of the thesis are

1. To develop valid and reliable methods, and associated measurement error for 2D kinematic and qualitative movement assessment tool, during two unilateral limb loading patterns
2. To establish what factors, impact the application of 2D and qualitative assessment in the youth adolescent population during unilateral loading tasks
3. To establish if performances of the unilateral loading tasks change over a competitive season or training period
4. To establish the effect of an educational piece on levels of rater agreement and consistency of rater methods

Chapter Three

3.0 Methodology

3.0 Reliability and Validity of 2D and Qualitative kinematics during 2 unilateral loading tasks

3.1 Introduction

Musculoskeletal (MSK) screening tools – particularly of the lower limb (LL) – are widely used within clinical and sporting environments to highlight injury risk susceptibility and influence the composition of rehabilitation and conditioning programming and return to play (RTP) guidelines (Bahr, Clarsen and Ekstrand, 2018). The assessment of movement quality by practitioners is vastly gaining ground within clinical practice, due to the contributing factor diminished or suboptimal movement quality is believed to have on injury risk (Chmielewski *et al.*, 2007; Maclachlan, White and Reid, 2015; Whittaker *et al.*, 2017). Research has continued to show associations between movement variability and MSK injury (Baida *et al.*, 2018). (Therefore, movement quality is considered to be a modifiable factor that clinicians can impact to reduce injury risk.

The analysis of human movement is widely utilised in sport and both quantitive and qualitative techniques are deployed within its analysis. Laboratory-based three-dimensional (3D) analysis is purveyed as the "Gold Standard" within most literature, due to its ability to provide researchers and clinicians with reliable data on multiplanar forces and angles at the joint during a variety of basic to complex movements (Bohn *et al.*, 2016; Schurr *et al.*, 2017). 3D technology in the non-research environment is expensive, time consuming and often unfeasible to set-up. Due to sophisticated equipment requirements, financial and time costs involved in data collection and analysis, along with the real-world need to capture large numbers of participants with frequently, 2D video analysis and Qualitative Visual Rating Criteria have emerged as a cheaper, portable, more accessible means of human movement analysis (Schurr *et al.*, 2017).

2D movement analysis has been demonstrated as a useful alternative to the 3D method. Work by several authors (Willson and Davis, 2008; Ekegren *et al.*, 2009; Munro, Herrington and

Carolan, 2012; Maclachlan, White and Reid, 2015; Maykut *et al.*, 2015; Mostaed, Werner and Barrios, 2018), has demonstrated its reliability and validity is comparative to 3D, notably around FPPA and knee separation distance, during bilateral (Munro, Herrington and Carolan, 2012), unilateral (Edmondston *et al.*, 2013) and explosive (Ford, Myer and Hewett, 2007; Myer, Bates, *et al.*, 2015) lower limb tasks. Moderate to excellent Intraclass correlation (ICC) values have been reported for within-day (ICC = 0.59-0.88) and between day (ICC = 0.72-0.91) reliability for both parameters. Intra- and inter-rater reliability has also been shown to provide moderate-high (ICC = 0.89-0.99) reliability results across a range of practitioner experience from novice to expert raters during Single-Leg Land, Single-Leg Squat and drop-jump movements (Almangoush, Herrington and Jones, 2014; Tate *et al.*, 2015; Raïsänen *et al.*, 2016; Herrington *et al.*, 2017).

The above studies have only focused predominantly on frontal and sagittal lower limb parameters, this has left a considerable limitation within this body of research because of the absence of trunk and upper limb evaluation. Torso and Upper Limb positioning has been shown to influence the lower limb during landing (Williams *et al.*, 2017; De Blaiser *et al.*, 2018; Dingenen, Blandford, *et al.*, 2018) potentially impacting lower limb loading, patterning, movement quality and subsequent injury risk. Whilst these studies have begun to acknowledge the involvement of the upper quadrant to whole movement patterning, by highlighting the contributions and impact the torso and upper limb may have on the biomechanics on the lower limb. Protocols regarding the measurement and capturing of torso and upper limb movement within whole movement patterning are lacking. Additional investigation into developing a methodology via 2D and qualitative means is warranted, as these methods provide a practically feasible route for practitioners to identify if effective measurement is even possible before any potential further relationships can be established.

The 2D method has been shown as a valid and reliable clinical method in the absence of 3D analysis across athletic tasks and for practitioners of all abilities. 2D analysis is not without limitation, with some researchers questioning its capability to capture multiplanar elaborate motion (McLean, Huang and van den Bogert, 2005; Willson and Davis, 2008; Maykut *et al.*, 2015) . Qualitative means of evaluation of unilateral athletic movement tasks, share the feasible, easy application and minimal space requirements of 2D, but also allows navigation around the issue of evaluation of multiplanar movement, that 2D evaluation is often disadvantaged by. Several authors (Chmielewski *et al.*, 2007; Ekegren *et al.*, 2009; Padua *et al.*, 2009; Crossley *et al.*, 2011; Whatman, Hume and Hing, 2013) have explored and cultivated the use of lower limb qualitative visual scales during functional movements, to provide clinicians with an appropriate, simply applied means of addressing movement quality issues within the MSK system that may contribute to injury risk.

Traditionally, qualitative methods are considered inferior to 3D methods due to questions around the ability to identify high-risk participants (Ekegren *et al.*, 2009) and rater subjectivity. The Landing Error Scoring System (LESS) was initially developed to identify non-contact ACL injury within military subjects. Through evaluation of a jump landing technique (Padua *et al.*, 2009), it is a well-known tool deployed in clinical practice. It has shown good inter-rater reliability (ICC =0.72-0.81) with the standard error of measurement (SEM) ranging from 0.69-0.79 points (Padua *et al.*, 2009, 2011; Chimera and Warren, 2016). Similarly, later work by Harris-Hayes *et al.*, (2014) also demonstrated excellent inter-rater reliability (ICC = 0.75-0.90) of visual rating criteria of a single leg squat by novice and expert practitioners. Whilst the LESS system has been shown to be a valid and reliable clinical tool, that demonstrates minimum set-up time and efficient post-test evaluation, analysis of trunk position is limited. There is no evaluation or consideration of the upper limb, and the system remains limited to evaluation of bilateral jumping movements only.

The Qualitative Analysis of Single Leg Loading (QASLS) is a relatively new clinical assessment tool for single-leg load tasks (Herrington and Munro, 2014). Using an uncomplicated segmental system to evaluate movement quality, it aims to advance persistence, accurate, practitioner usability in daily practise. The QASLS system incorporates ratings of both the torso and upper limb during unilateral single leg tasks. This allows for comparison between limbs but is also arguably more replicative of the unilateral patterns seen in sport (such as hopping, change of direction and landing). Unilateral limb evaluation is important because it remains the most common mechanism of the majority of lower limb overuse and traumatic occurrence injuries (Whatman, Hume and Hing, 2013), and the effective evaluation of unilateral movement quality provides valuable markers for identifying both sporting and non-sporting individuals at risk of injury.

Almangoush, Herrington and Jones, (2014) showed that 4 senior expert raters were able to reliably (PEA: 83-100%,κ = 0.63-1.0) utilise QASLS during a single leg squat task, with almost perfect/excellent (PEA:95-100%,κ=0.89-1.0) intra-rater reliability. Herrington and Munro, (2014) also sought to establish criterion validity of single-leg squat and single-leg land to 3D kinematics reporting excellent association for single-leg squat (PEA = 98.4%, κ = 0.97) and single-leg land (PEA = 97.1%, κ = 0.90) against 3D motion capture. QASLS is also provisionally recommended within a systematic review (Wilke, Pfeiffer and Froböse, 2017) as a potential time-efficient preliminary assessment, however, the authors do advise caution due to paucity of research regarding its use. Whilst the above research provides insight and grounding in the reliability and validity of the QASLS system, studies are limited to small numbers of participants ($\leq$ 5), and at present provide no insight into measurement error.

Measurement error values are an integral element of understanding the value of a tool, task or intervention. As they inform a clinician that any notable changes occurred are representative of a truly observed change and not attributed to systematic error, chance or an intervention. Whilst ICCs allude to the reliability, they remain insensitive to sample variety (Koo and Li, 2016). It is therefore recommended that a standard error of measurement (SEM) and the smallest detectable difference (SDD) also be presented to accurately identify and establish parameters to classify changes in performance. The SEM informs clinicians of the measurement error of a test, is presented in the same units as the measurements and therefore allows scrutiny to other SEM presented within the literature. The SDD provides a base value which should be surpassed to distinguish real change from random error.

3.1.2. Validity

Confirming the reliability of a test or tool is not only important in identifying true and absolute changes in performance for a practitioner, but the establishment of reliability is also imperative for the corroboration of test validity (Batterham and George, 2003). Qualitative movement assessment tools may well provide an alternative means to 3D and 2D analysis. Qualitative scoring systems have begun to establish criterion validity during bilateral landings (Ekegren *et al.*, 2009; Onate *et al.*, 2010), single-leg squats (Ekegren *et al.*, 2009; Whatman, Hume and Hing, 2013; Herrington and Munro, 2014) and single-leg lands (Herrington and Munro, 2014), the research body still lacks scientific information regarding reliability and validity of the tool. Given that 3D motion-capture remains an un-viable choice for most practitioners and researchers (as explained in chapter 2), qualitative systems must correlate to some kind of movement quality measurements (such as 2D) to identify any correlations to movements associated with injury risk.

Similarly, only the relationships between 2D frontal plane projection angles (FPPA), hip adduction angles, and qualitative scores has been investigated. Whilst a limited number of studies have examined 2D trunk lean measurements to 3D motion analysis (Dingenen *et al.*, 2014; Plummer *et al.*, 2018) none have compared 2D trunk lean measurements to the more accessible qualitative analysis. Given the influence of trunk lean to the lower limb during single-leg loading and increases in turning moments (Dingenen, Staes, *et al.*, 2018) and injury risk. Further investigation of the trunk lean parameter via 2D and qualitative methods is imperative. Upper limb and shoulder kinematics do not appear to have been systematically examined via any 3D, 2D or qualitative methods during single-leg loading tasks. Lower limb movement patterning is greatly influenced by body position as a whole, it is not illogical to presume that the upper limb would contribute to this, therefore further investigation around the reliability of trunk and upper limb 2D qualitative parameters is required before it can be wholly recommended in the use of movement quality screening tasks.

To date, only one paper has attempted to establish the validity of the QASLS assessment tool (Herrington and Munro, 2014). With the authors of this study concluding that although additional work on a larger scale was required to establish reliability and sensitivity, there was strong criterion validity comparative to 3D motion capture for single leg tasks. As this is currently the only paper, further comparisons of the QASLS system per-say is not presently possible. Other qualitative systems such as the LESS have also established criterion validity compared to kinematic 3D data collection (Padua *et al.*, 2009, 2011; Onate *et al.*, 2010; Everard, Lyons and Harrison, 2018). Correlations between 2D data and qualitative systems must be evident to demonstrate that the tool shows those that might be displaying movement quality patterns that are associated with injury risk. Whilst relationships between 2D and 3D parameters have been shown for certain bilateral tasks, whether the relationship between 2D and qualitative QASLS observation exists is presently unknown.

Currently, no investigation has documented measurement error values or within and between session values of the QASLS system. If the measurement error, reliability and validity of the qualitative method can be established, practitioners will be able to use the QASLS system with certainty. This will assist with informing observation around individual and group performances, movement variability and associated injury risk, to support the development of better profiling practises.

Therefore, the aims of this study where to complete the development and investigate the utility of a qualitative profiling tool for movement quality affiliated to the complex systems approaches identified within the literature review. Through the establishment of intra-rater, inter-rater, within-session and between-session reliability and measurement error for the 2D kinematic variables and the qualitative assessment tool QASLS. With the secondary aim of establishing the validity of the qualitative rating tool against the criterion 2D measurements during the unilateral movement assessment tasks of single-leg squat and single-leg land. It was hypothesised that both the 2D kinematics and QASLS scores would demonstrate good to excellent within and between-session reliability for both unilateral tasks. It was also hypothesised that the 2D parameters and QASLS tool would show good to excellent intra-rater and inter-rater reliability during both movement tasks, however, it was expected that inter-rater reliability would demonstrate more variability depending on rater experience. Finally, it was hypothesised that the QASLS tool would have strong relationship validity when compared to the 2D kinematic motion capture.

3.2 Methods

3.2.1 Test Space Set-Up

Based on the previous pilot work (Chapter 8 -Supplementary A), wooden plyometric boxes were constructed to 30cm height. Testing space was configured (figure 3.1) following pilot work results (Chapter 8 - Supplementary A-C) with cameras placed 3 meters from the testing/landing zone in both the frontal and sagittal planes, and set upon tripods set to a height of 0.7m, with each camera levelled via bubble inclinometer on the tripod Calibration frames were taken in both planes with a calibration frame placed on the middle of the "H" as this was considered the landing zone for participants. This set up was then the standardised procedure used for the duration of testing through this research where 2D kinematics and or qualitative measurements were collected.

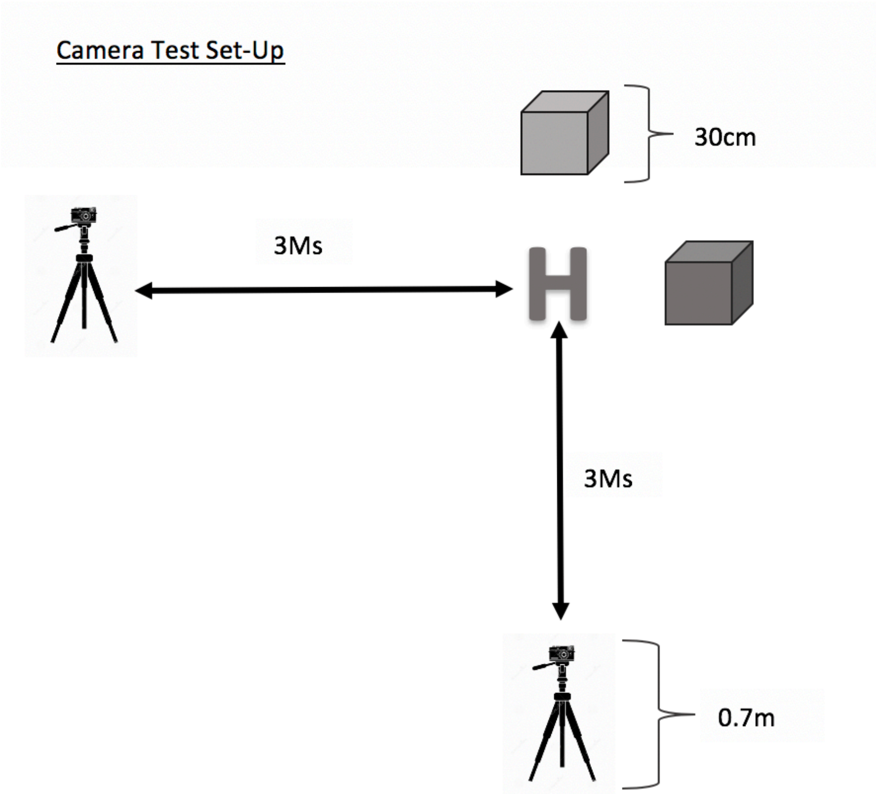


Figure: 3.1 Camera and Plyobox Placement during Single Leg Load Tasks

Participants

15 vocationally trained elite pre-professional (Coutinho, Mesquita and Fonseca, 2016) female dancers, (age 19±2 height 167±6 cm body mass 56±6 kg), volunteered for this study. Participants were required to be free from injury and have no history of surgical intervention within the last 6 months. Participants provided written informed consent before data collection. The study was approved by the University of Salford Research and Ethics Committee and was completed within the spirit of the declaration of Helsinki (1983).

3.2.2 Research Design

The study was completed following a repeated measures experimental design, participants attended testing within their performance facility on 3 separate occasions during a three-week testing period. Within-session data collection occurred on the same day with session 2 occurring one hour after session 1, and between-session data collection occurred one week later. All testing sessions were conducted at the same time of day to account for circadian rhythm changes that may affect performance tasks.

During the first two testing sessions, participants performed single-leg squat (SLS) and single-leg land (SLL) on both the right and left legs and 1 repetition of the tuck jump assessment (TJA). The order of the movement tasks randomly selected (by participants selecting face down cards that had the tasks written on in random orders) in session 1. This was repeated in session 2 as this allowed within-session reliability to be determined. During the third testing session, participants performed SLS and SLL on both the right and left legs and 1 repetition of TJA[1], task order was re-randomised, which allowed between-session reliability to be determined.

3.2.3 Protocol

Before data collection, 23 anatomical landmarks (figure 3.2) were identified (Chapter 8 - Supplementary D) and marked with a marker on the subject's skin on the upper limb, lower limb and torso to approximate the landmarks employed by previous research (Willson and Davis, 2008; Munro, Herrington and Carolan, 2012; Dingenen *et al.*, 2014; Schurr *et al.*, 2017). Markers were placed on the midpoint (as determined by tape measure) of the femoral condyles to approximate the centre of the knee joint, ankle joint centre was defined as the midpoint of the medial and lateral malleoli markers.

[1]Note: When the PhD was being conceptualised, and following on from the literature review, it was expected that due to the qualitative nature of the Tuck Jump Assessment, it would be analysed as part of the methodology. It was therefore examined and investigated further and was included as part of the protocol in pilot and original data collection. However further data set analysis revealed that there was little corroboration between the double leg TJA task and unilateral SLS and SLS tasks. As the TJA did not appear to be necessarily comparable to the unilateral tasks and potentially acted as a further confounding factor, it was decided that future data analysis would be conducted using the unilateral tasks only and the TJA data retained for post-doctoral analysis as a separate body of data.

The FPPA was taken as the line from the proximal thigh to the knee joint and the line from the knee joint to the ankle. Lateral Trunk flexion the angle between a vertical line starting at the ipsilateral anterior superior iliac spine (ASIS) and the line between the ipsilateral ASIS and the sternum. Hip flexion was measured as the angle between the acromion clavicular joint (ACJ) and lateral knee joint with the greater trochanter and lateral knee joint line. Ankle dorsiflexion angle between lateral knee joint to the lateral malleolus and a line parallel with the 5th metatarsal. Shoulder extension was calculated as the angle from a line bisecting the ACJ to the iliac crest of the hip and ACJ to radial styloid. All markers were applied by the same clinician (GP) for each participant.

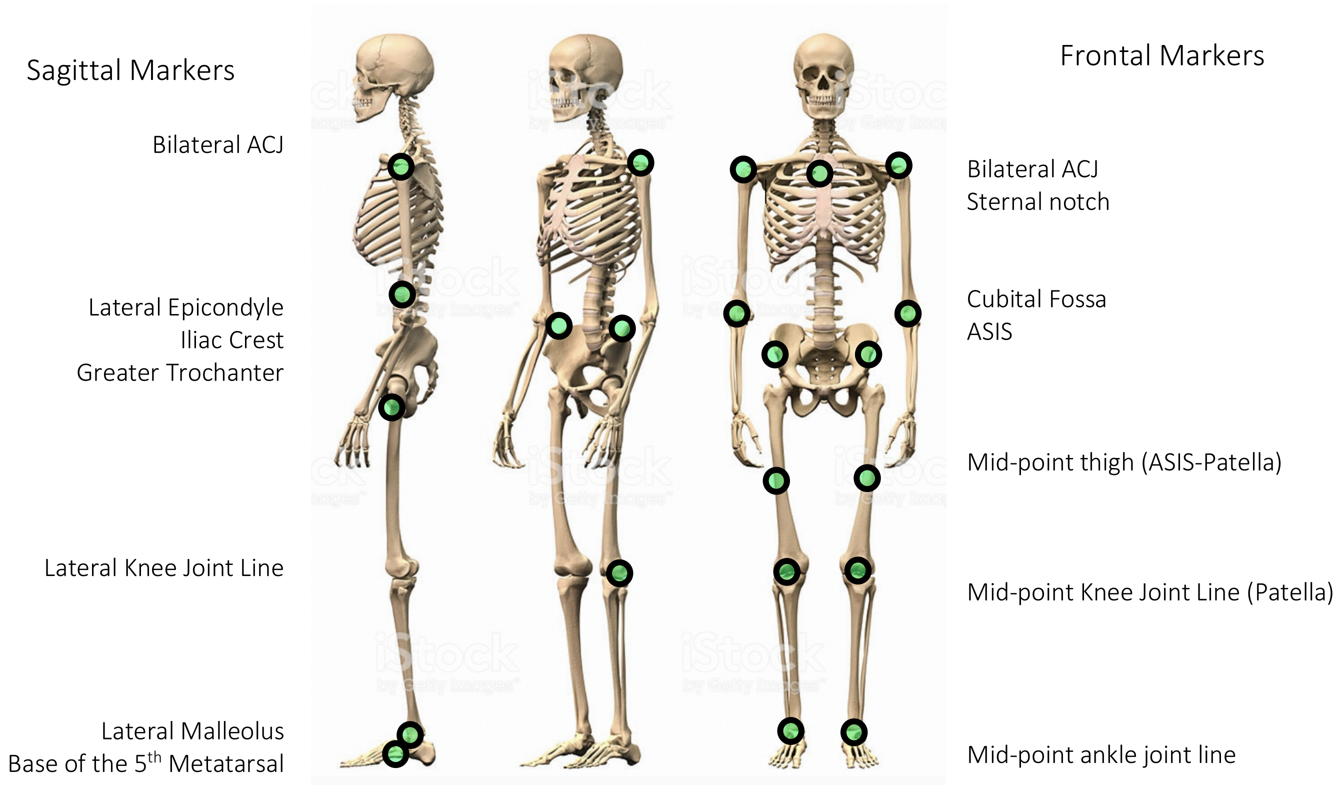


Figure 3.2 2D marker selection positions

3.2.4 Movement Assessment Tasks

Single-Leg Squat (SLS) (Figure 3.3)

Participants were asked to stand on 1 limb (self-selected) facing the frontal plane, they were verbally instructed to squat as low as possible as if sitting back and down on a chair and return to the start position. Participants were then asked to repeat on the opposite limb. No further instructions were provided so as not to influence the individual's movement strategy.

Single-Leg Land (SLL) (Figure 3.4)

Participants stood on a 30cm high plyometric box, they were asked to step forward and land onto the contralateral limb holding landing for at least 2 seconds. As with the SLS, no further instructions were provided so as not to influence the individual's movement strategy.

Figure 3.3 Single-leg squat frontal and sagittal view

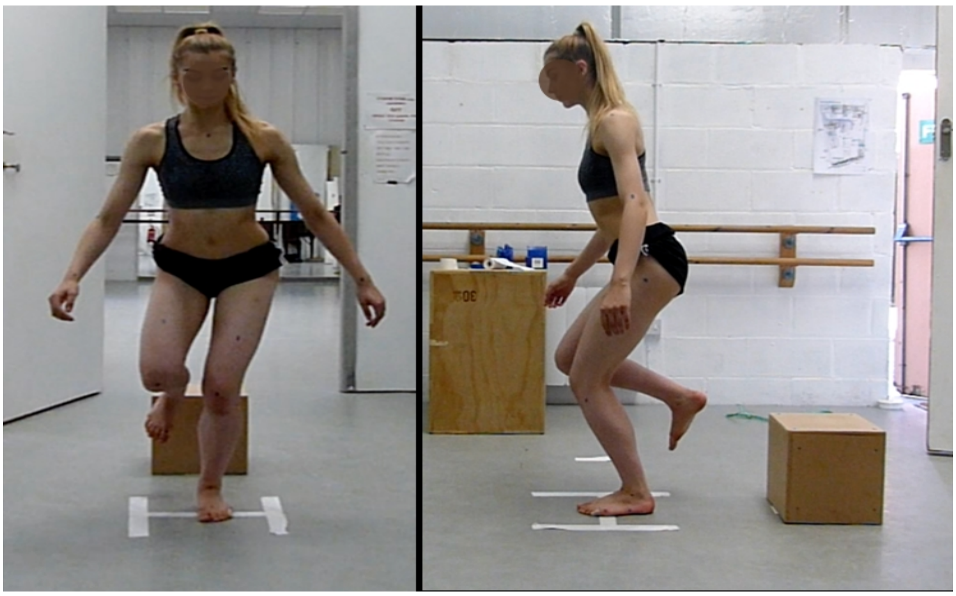


Figure 3.4 Single-leg land frontal and sagittal view

3.2.5. 2D Analysis

Two digital cameras (Panasonic Lumix DMC-FZ200) collected video for 2D data analysis collecting at a sampling rate of 100 Hz, which was then saved to a computer for later analysis. The previously mentioned markers were used to digitise angles using Quintec Biomechanics software (9.10 version 25) to allow for frontal measurements of Shoulder Abduction (SABN), Lateral Trunk Lean (LTL), Hip Adduction Angle (HADD), FPPA and sagittal movement of Shoulder Extension (SEN), Trunk Flexion Angle (TFA), Hip Flexion Angle (HFA), Knee Flexion Angle (KFA), and Ankle Dorsiflexion (ADF). All angles were taken at the frame that coincided with the maximal knee flexion (which was determined as the deepest part of the movement) of the movement assessment tasks. The average of each parameter from the 5 trials was used for analysis, the same analysis was undertaken to obtain the 2D kinematic angles in the rest of this PhD. The methods of kinematic extraction from Quintec were determined following pilot work (Chapter 8 - Supplementary B-C), the concluding version is described below.

3.2.6. Measurement of each 2D Kinematic Parameter on Quintec

3.2.6.1 The Frontal Plane

Shoulder Abduction (SABN): Was measured from a known vertical line from the acromion clavicular joint (ACJ) to mid-point of the elbow joint line (cubital fossa position)

Figure: 3.5 Example of 2D shoulder abduction measurement

Lateral Trunk Lean (LTL): Was measured from the lateral shoulder joint centre and lateral ASIS landmarks and a vertical line that intersects the lateral ASIS (DiCesare *et al.*, 2014; Dingenen *et al.*, 2014).

Figure: 3.6 Example of 2D Lateral Trunk Lean measurement

Hip Adduction Angle (HADD): Was measured as the angle from a line drawn from the none WB ASIS to WB ASIS, then from WB ASIS to mid-point proximal thigh markers towards patella marker (Herrington *et al.*, 2017).

Figure: 3.7 Example of 2D Hip Adduction angle measurement

Frontal Plane Projection Angle (FPPA): Was measured as the angle between a line drawn from proximal thigh to knee joint, line from knee joint to ankle (Munro, Herrington and Carolan, 2012).

Figure: 3.8 Example of 2D FPPA measurement

3.2.6.2 The Sagittal Plane

Shoulder Flexion/Extension (SEN): Was measured as the angle from a line drawn from the Iliac crest marker to ACJ, then draw ACJ to lateral epicondyle marker

Figure: 3.9 Example of 2D sagittal shoulder angle measurement

Trunk Flexion Angle (TFA): Was measured as the angle from a line drawn from the sternal notch (mid torso) to greater trochanter) to a known vertical (Schurr *et al.*, 2017).

Figure: 3.10 Example of 2D sagittal trunk lean measurement

Hip Flexion Angle (HFA): Was measured as the angle from a line drawn from ACJ to greater trochanter, then greater trochanter to lateral knee joint line (Schurr *et al.*, 2017).

Figure: 3.11 Example of 2D sagittal hip flexion angle measurement

Knee Flexion Angle (KFA): Was measured as the angle from a line drawn from greater trochanter to lateral knee joint line, then knee joint line to lateral malleolus (Padua *et al.*, 2009)

Figure: 3.12 Example of 2D sagittal knee flexion angle measurement

Ankle Dorsiflexion Angle (ADF): Was measured as the angle from lines drawn from the lateral knee joint line to lateral malleolus to floor, then floor to 5th metatarsal (Norcross *et al.*, 2011; Timothy C. Mauntel *et al.*, 2013).

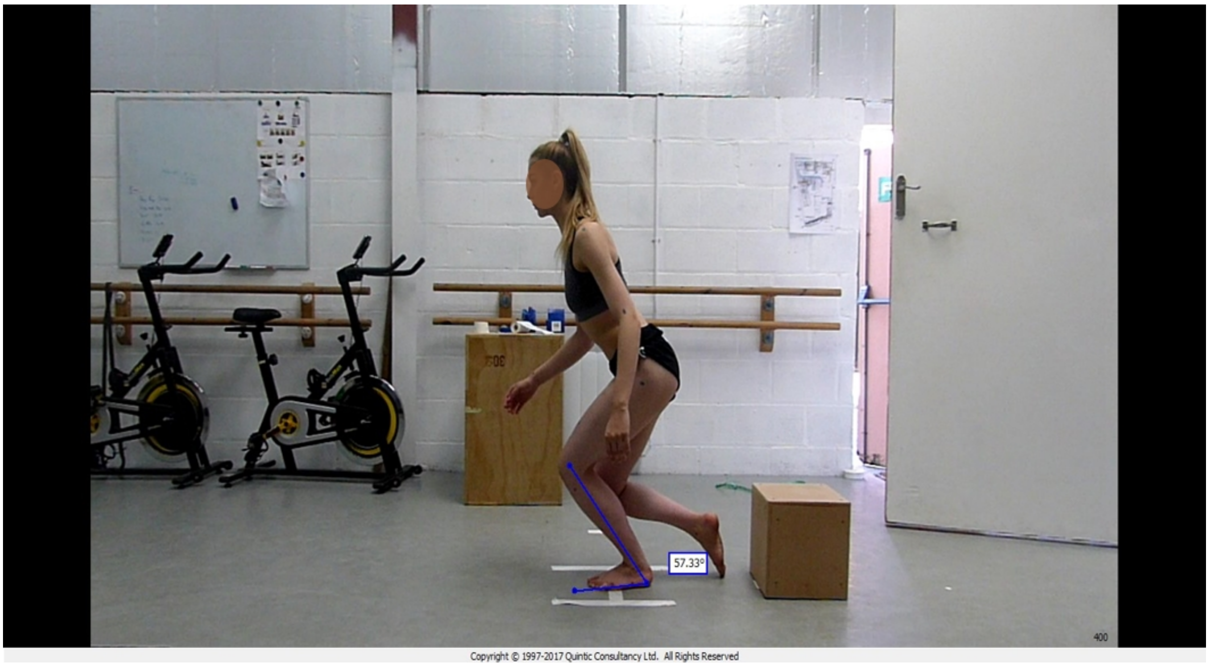


Figure: 3.13 Example of 2D sagittal ankle flexion angle measurement

3.2.7 Statistical Analysis

All statistical analysis was conducted using SPSS for Windows (version 25) (SPSS Inc, Chicago, IL.), data for each 2D variable satisfied criteria for parametric testing in relation to normality via Shapiro-Wilk test. The frontal and sagittal 2D parameters were measured via ICCs. Each 2D variable expressed is representative of the mean and standard deviation of the mean value of all 5 trials for each participant, with p-value set as $p=0.05$. The standard error of measurement (SEM) and Smallest Detectable Difference (SDD) was calculated to represent and establish the smallest clinically worthwhile change and identify random error scores between test sessions. Previously reported methods (Munro, Herrington and Carolan, 2012; Herrington and Munro, 2014; Herrington *et al.*, 2017). Munro, Herrington and Carolan, (2012) methods were used to calculate SEM and SDD via the following formulas respectively.

$$SD\,[pooled] \times \sqrt{1-ICC}$$
$$1.96 \times \sqrt{2} \times SEM$$

Within test and between test reliability 2D Variables

The same tester (GP) analysed each trial, within-day reliability was assessed from the data from session 1 and session 2 and test-retest reliability was assessed from data from session 1 and session 3, ICCs (2,1) were used to measure the within and between-session reliability of the 2D variables of each limb and movement assessment tasks, with 95% confidence intervals (CI) SEM and SDD extrapolated from each value. ICC values were interpreted according to previously published data (Koo and Li, 2016) where values greater than 0.75 were considered good to excellent.

Intra-rater reliability of 2D Variables

Single rater analysis was determined using the above ICC model and SEM. The previous tester (GP) was used to assess trial 1 of all participants, before repeating the same analysis of the same trial a month later. A month was chosen as it fitted data collection time-frames and was also considered to be an adequate amount of time to eliminate recollection of the previous analysis.

Inter-tester reliability of 2D Variables

Data collected from data collection session 1 was used to analyse inter-rater reliability. A second rater (BO) was provided with written and photographic instruction (figures 3.6-3.14) to analyse the 2D parameters through the Quintec software, which were the same as those used by GP. To avoid bias neither rater knew of the others scores, reliability between both raters was analysed via the ICC (3,1) model.

Qualitative Rating Criteria Analysis via QASLS

The QASLS is a visual rating tool that provides a segmental scoring approach of an observed unilateral loaded movement pattern such as a squat or land. Adopting a dichotomous scoring strategy of six body segments (Arm, Trunk, Pelvis, Hip Knee and Ankle), the tool utilises a region criteria where appropriate strategy scores a zero and suboptimal strategy scores a 1. A higher QASLS score indicated a greater number of component strategies used to complete a unilateral loading task, and a lower QASLS score indicated a lesser number of component strategies required to complete the unilateral loading tasks. The videos collected during 2D data collection were analysed using QASLS scoring sheet (figure 3.15), the scoring performance was derived for each participant from both the frontal and sagittal plane views, with each video viewed then marked and scored. Pilot data collected previously (Chapter 8 - Supplementary D) indicated that 2D markers do not appear to influence compound qualitative scoring.

Within test and between test reliability Qualitative Rating Criteria – QASLS

Similar to the 2D kinematic data analysis, the same tester (GP) analysed each trial. Within day reliability was assessed from the data from sessions 1 and 2 and between session from session 1 and 3. ICCs were selected to measure the within and between-session reliability and agreement (Hernaez, 2015) of the QASLS scores of each of the limbs and movement assessment tasks, with 95% CI and SEM, SDD values reported. Within and between-session reliability of composite scores were calculated using a mean rating (κ=3) 2-way mixed-effects absolute agreement model. Koo and Li, (2016), scale was selected to interpret ICC value with > 0.90 excellent, 0.75-0.9 as good, 0.50-0.75 as moderate, and < 0.50 as poor.

Qualitative analysis of single leg loading

Date: Patient:

Condition: Left Right Bilateral

QASLS	Task: Single leg squat Single leg step down Single leg hop for dist	Left	Right
Arm strategy	Excessive arm movement to balance		
Trunk alignment	Leaning in any direction		
Pelvic plane	Loss of horizontal plane		
	Excessive tilt or rotation		
Thigh motion	WB thigh moves into hip adduction		
	NWB thigh not held in neutral		
Knee position	Patella pointing towards 2^{nd} toe (noticeable valgus)		
	Patella pointing past inside of foot (significant valgus)		
Steady stance	Touches down with NWB foot		
	Stance leg wobbles noticeably		
	Total		

Figure 3.14 QASLS Scoring Sheet

Intra-rater reliability of Qualitative Rating Criteria – QASLS

Single rater analysis was determined via the percentage of exact agreement (PEA) [PEA= (agreed/agreed+disagree) x 100] and kappa coefficients, where the equation for κ was

$$\kappa = \frac{Pr(a) - Pr(e)}{1 - Pr(e)}$$

Where Pr(a) is the relative observed agreement among raters, and Pr(e) is the hypothetical probability of chance agreement, using the observed data to calculate the probabilities of each observer randomly selecting each category (Herrington, Myer and Munro, 2013). When scoring performance, each participants video was played as frequently and at the speed deemed necessary by the tester that they required to obtain a score.

Inter-rater reliability of Qualitative Rating Criteria – QASLS

Due to the dichotomous nature of the QASLS system (de Vet *et al.*, 2006; Hernaez, 2015), PEA and kappa coefficient were used to determine the reliability of QASLS. Three raters (LH, AM and BO) independently scored participants across the 5 trials via QASLS scoring sheet. Each trial was viewed from dual-plane of frontal and sagittal as many times and speed the raters required to obtain a score. The three raters were provided with written instructions on how to assess the movement tasks via QASLS and were blinded to the other raters scores, to avoid potential bias. A fourth investigator (GP) who was blind to the identity of the raters, analysed the score for all raters for each participant. Cohens Scales(McHugh, 2012) were selected to interpret κ-values of both the intra and inter tester reliability. Where 0.81-1.00 is an almost perfect agreement, 0.61-0.80 is substantial, 0.41-0.61 moderate, 0.21-0.40 as fair and 0.01-0.20 as none to slight. Acceptable percentage of exact agreement (PEA%) has been described in the literature (Stemler 2004) as between 75-90%, however, this figure remains very specific to each study. For this paper, an agreement of $\geq$ 66% has been chosen as acceptable.

Validity – Relationships between 2D Parameters and QASLS Dichotomous score

Construct validity was determined from data collected over each repetition from all 14 participants on each of the three test occasions (n=420), analysis was carried out on both limbs and landing tasks. Due to reliability results from 2D parameters and direct comparators from 2D parameters to QASLS components, only the 2D variables of Lateral Trunk Lean (LTL), Trunk Flexion Angle (TFA), Hip Adduction Angle (HADD) and FPPA were taken forward into validity analysis. All data were normally distributed. Correlations between 2D LTL, TFA, HADD, FPPA and QASLS components (Qu 2,5,7,8) were analysed using Spearman's Correlation Co-Efficient (rs) preliminary analysis showed relationships to be monotonic, as assessed by visual inspection of scatterplots, with statistical significance set a $p < 0.05$. Correlations were interpreted by the recommendations of Schober, Boer and Schwarte, (2018) where <0.10 is negligible, 0.10-0.39 weak, 0.40-0.69 moderate, 0.70-0.89 strong, and > 0.90 very strong. Receiver Operating Characteristics (ROC) curves were calculated for the continuous 2D variables to determine the ability of the QASLS tool to identify those with trunk lean, hip adduction and knee valgus, with sensitivity and specificity, also presented. In line with research recommendations (Sedgwick, 2015; Bahr, Clarsen and Ekstrand, 2018), cut off values are also presented.

3.3 Results

15 Participants met the inclusion criteria, 1 participants data were excluded from the study due to corrupted video data resulting in an analysis of 14 participants.

Within-Session and Between Reliability of 2D Kinematic Parameters (Tables 3.1-3.4)

There were no significant differences noted between limbs (p >0.05) or between testing sessions for any 2D parameter. Within–session reliability of 2D frontal and sagittal parameters for both the single leg squat (Table 3.1) and single-leg land (Table 3.2) was good-excellent, except for shoulder abduction (0.61-0.67) and lateral trunk lean right (0.74) graded as moderate, and shoulder extension (0.10-0.19) graded as poor during a single-leg squat. FPPA Left (0.66) and Shoulder Extension Left (0.60) graded as moderate during single-leg land. SEM values ranged from 0.7-7.2° and the % SDD's from 2.3-7.9°for single-leg squat. SEM values ranged from 0.9-4.1° and the % of SDD's from 2.6-5.6° for single-leg land. Between session reliability of 2D frontal and sagittal parameters for both unilateral tasks were generally lower but overall was considered to be moderate to good with ICCs ranging from 0.52-0.83 for single-leg squat (Table 3.3) and 0.51-0.91 for single-leg land (Table 3.4). Furthermore, SEM values ranged from 1.3-10.1° and the % of SDD 3.6-27.9° for single-leg squat and 1.7-8.4° and % of SDD 8.8-23.3° for single-leg land respectively.

Again, both frontal and sagittal parameters of the shoulder were graded as poor (0.07-0.32) during a single leg squat as were knee flexion angle (0.15) and ankle dorsiflexion angle (0.16) on the right. Lateral trunk lean right (0.48) and shoulder extension left (0.48) were graded as poor during single-leg land.

Intra-Rater Reliability of 2D Kinematic Parameters (Tables 3.5-3.6)

Intra-rater reliability for single leg squat is presented in Table (3.5) and Table (3.6) for single leg land. ICCs ranged from 0.73-0.99 and were graded as moderate to excellent for frontal parameters during single leg squat, sagittal parameters were also graded as good-excellent (0.80-0.93) with the exception of shoulder extension left limb (0.23) and ankle dorsiflexion of the right limb (0.38). SEM scores ranged from 0.4-8.5° demonstrating small measurement error. Despite good ICC values (0.80-0.87), hip flexion angle demonstrated high SEM (5.3-8.5°) with a substantially high %SDD (14.8.-23.6°), and therefore random measurement error cannot be discounted for this parameter.

Intra-rater reliability for single leg land was found to be excellent (0.94-0.99) for all sagittal parameters and good to excellent (0.80-0.97) for all frontal parameters with lateral trunk lean Left (0.66) and hip adduction left (0.72) graded as moderate. SEM scores ranged from 0.2-3.4° demonstrating very little measurement error.

Inter-Rater Reliability of 2D Kinematic Parameters (Tables 3.7-3.8)

Inter-rater reliability for the single-leg squat is presented in Table (3.7) and Table (3.8) for single-leg land. Reliability was deemed moderate to excellent for SLS (ICC =0.71-0.99) and SLL (ICC = 0.66-0.98). SEM scores ranged from 0.3-10.5° highlighting small measurement error. Hip flexion angle is the exception to this due to SEM scores of 10.1-10.5° that again had a large %SDD (28.0-.29.1°) and are potentially subject to measurement error.

Within- Session and Between Reliability of QASLS (Tables 3.9-3.10)

There were no significant differences noted between limbs ($p > 0.05$) or between testing sessions for single-leg land or single leg squat. Within and between-session reliability for both single leg tasks were moderate to excellent (ICC = 0.67-0.93). The within-day reliability of the QASLS composite score (0-10) for single-leg squat resulted in an ICC of 0.82 (95%CI = .36-.96) for the right limb and 0.86 (95%CI = .49-.97) for the left and was graded as good. The SEM for within-day reliability was 0.82 and 0.72 points the SDD 2.28 and 2.00 points on a ten-point scale for the right and left limbs respectively. Similar results were observed in the single-leg land task of the right limb (ICC = 0.87, 95% CI .42-.97, SEM 0.45, SDD 1.26) however an ICC of 0.67 (95%CI .25-.92, SEM 0.89, SDD 2.45) was observed in the left limb which was noted as moderate. The between-session reliability (completed at 7 days post) of the composite QASLS score for the single-leg land was slightly less compared to the within-session scores (Right Limb ICC= 0.72 95%CI .15-.93, Left Limb ICC = 0.69 95%CI .07-.92) and was graded as moderate.

The between-session reliability (completed at 7 days post) of the composite QASLS score for the single-leg land was slightly less compared to the within-session scores (Right Limb ICC= 0.72 95%CI .15-.93, Left Limb ICC = 0.69 95%CI .07-.92) and was graded as moderate. The SEM for single-leg squat between-session reliability was 0.96 and 0.99, the SDD was 2.65 and 2.75 for the right and left limbs. The single-leg land task demonstrated greater between-session reliability (ICC = 0.92-0.93) with SEM of 0.41 and SDD of 1.14 for the right limb and 0.47 and 1.52 for the left limb. All SEMs for both within-session and between-session (except the left limb on single leg land between session) were less than 1 with the SDD ranging from 1.0-2.5 points on the 10-point scale. This suggests an error measurement of 1 across testing time frames and that a change of 1-3 points would be necessary to demonstrate a real change in unilateral loading performance over time.

Table: 3.1 Within-session reliability of Single Leg Squat

FRONTAL PARAMETERS	TEST 1 (°)	TEST 2 (°)	ICC	CV%	95% (CI)	SEM (°)	SDD (°)
Shoulder Abduction Right	9.4 ± 5.3	8.7 ± 4.2	0.697	22.0	(.122 -.922)	2.6	4.5
Left	8.9 ± 6.5	8.6 ± 3.5	0.667	22.9	(.037 -.951)	2.9	4.7
Lateral Trunk Lean Right	25.7 ± 3.6	25.4 ± 5.1	0.736	1.8	(.181 -.934)	2.2	4.1
Left	24.7 ± 5.1	24.5 ± 4.8	0.982	0.5	(.919 -.996)	0.7	2.3
Hip Adduction Right	81.7 ± 4.1	88.7 ± 6.1	0.935	2.2	(.688 -.986)	1.3	3.2
Left	76.1 ± 7.7	79.5 ± 4.8	0.780	3.3	(.334 -.945)	2.9	4.7
FPPA Right	6.7 ± 4.7	5.7 ± 4.7	0.925	1.4	(.709 -.983)	1.3	3.1
Left	7.7 ± 4.1	4.8 ± 2.8	0.907	1.2	(.645-.978)	1.1	2.8
SAGITTAL PARAMETERS							
Shoulder Extension Right	12.6 ± 6.5	9.9 ± 3.3	0.691	30.4	(.632 -.693)	4.7	6.0
Left	9.4 ± 2.3	9.4 ± 2.3	0.194	20.0	(.050-.740)	2.1	4.0
Trunk Flexion Angle Right	28.6 ± 11.2	30.1 ± 13.3	0.895	8.7	(.625 -.975)	4.0	5.5
Left	28.6 ± 10.6	29.2 ± 13.8	0.950	8.0	(.779-.990)	2.7	4.6
Hip Flexion Angle Right	120.4 ± 9.6	125.2 ± 19.0	0.861	6.1	(.445-.971)	6.5	7.1
Left	118.2 ± 12.6	124.1 ± 21.1	0.763	6.5	(.296-.940)	7.2	7.9
Knee Flexion Angle Right	109.4 ± 9.6	108.5 ± 6.3	0.969	1.3	(.854-.994)	1.4	3.3
Left	108.5 ± 6.3	107.2 ± 8.9	0.806	2.4	(.375-.952)	3.3	5.1
Ankle Dorsiflexion Right	55.8 ± 4.6	55.7 ± 4.6	0.890	3.7	(.558-.977)	1.5	3.4
Left	54.0 ± 5.3	54.5 ± 5.1	0.884	2.5	(.589-.972)	1.8	3.7

CI= confidence intervals, CV% = Coefficient of variance, SDD = smallest detectable difference, SEM = standard error of measurement

Table: 3.2 Within-session reliability of Single Leg Land

FRONTAL PARAMETERS	**TEST 1 (°)**	**TEST 2 (°)**	**ICC**	**CV%**	**95% (CI)**	**SEM (°)**	**SDD (°)**
Shoulder Abduction Right	17.9 ± 10.1	16.1 ± 8.8	0.908	14.9	(.664 -.978)	2.9	4.7
Left	15.3 ± 8.9	14.5 ± 10.2	0.890	19.3	(.596-.974)	3.2	4.9
Lateral Trunk Lean Right	24.7 ± 5.5	25.0 ± 4.6	0.968	2.9	(.872 -.993)	0.9	2.6
Left	23.0 ± 4.2	24.0 ± 4.5	0.890	3.9	(.589-.974)	1.4	3.3
Hip Adduction Right	81.9 ± 6.8	80.3 ± 7.0	0.809	3.2	(.399 -.953)	3.0	4.8
Left	86.9 ± 6.8	81.3 ± 6.9	0.874	4.7	(546.-.971)	2.4	4.3
FPPA Right	11.6 ± 4.2	10.8 ± 4.3	0.864	14.7	(.382-.951)	1.6	3.5
Left	8.6 ± 5.1	7.3 ± 2.7	0.662	16.7	(.098-.910)	2.3	4.2
SAGITTAL PARAMETERS							
Shoulder Extension Right	15.2 ± 6.9	13.9 ± 6.0	0.900	12.2	(.639-.976)	2.0	4.0
Left	11.0 ± 8.4	10.0 ± 4.4	0.598	27.2	(.083-.894)	4.1	5.6
Trunk Flexion Angle Right	26.2 ± 13.7	25.9 ± 12.9	0.977	7.7	(.904-.955)	2.0	3.9
Left	25.2 ± 13.2	23.5 ± 13.9	0.966	10.8	(.853-.992)	2.5	4.4
Hip Flexion Angle Right	125.8 ± 14.7	124.8 ± 14.9	0.964	2.0	(.806-.992)	2.8	4.6
Left	124.2 ± 16.1	124.8 ± 14.9	0.939	2.8	(.757-.986)	3.8	5.4
Knee Flexion Angle Right	110.7 ± 8.2	108.6 ± 5.8	0.841	2.3	(.456-.961)	2.8	4.6
Left	111.0 ± 6.7	109.3 ± 6.8	0.885	1.8	(.568-.973)	2.3	4.2
Ankle Dorsiflexion Right	62.4 ± 5.3	6.7 ± 5.4	0.891	3.0	(.378-.956)	1.8	3.7
Left	62.3 ± 5.7	61.1 ± 5.5	0.878	2.2	(.546-.971)	2.0	3.9

CI= confidence intervals, CV% = Coefficient of variance, SDD = smallest detectable difference, SEM = standard error of measurement

Table: 3.3 Between-session reliability of Single Leg Squat

FRONTAL PARAMETERS	**TEST 1 (°)**	**TEST 3 (°)**	**ICC**	**CV%**	**95% (CI)**	**SEM (°)**	**SDD**
Shoulder Abduction Right	9.4± 5.3	8.2 ± 3.5	0.277	34.4	(.043-.770)	3.8	10.6
Left	8.9 ± 6.5	13.8 ± 5.5	0.317	51.4	(.390-.790)	5.0	13.8
Lateral Trunk Lean Right	25.7 ± 3.6	24.5 ± 3.7	0.569	7.4	(.055-.887)	2.4	6.6
Left	24.7 ± 5.1	23.6 ± 3.6	0.799	4.3	(.373-.950)	2.0	5.5
Hip Adduction Right	81.7 ± 4.1	82.5 ± 1.8	0.831	3.1	(.448-.958)	1.3	3.6
Left	76.1 ± 7.7	79.3 ± 5.2	0.765	4.8	(.302-.940)	3.2	8.9
FPPA Right	6.7 ± 4.7	6.1 ± 3.2	0.79	4.9	(.293-.949)	1.8	5.1
Left	7.7 ± 4.1	6.7 ± 3.1	0.645	4	(.020-.910)	2.2	6.0
SAGITTAL PARAMETERS							
Shoulder Extension Right	12.6 ± 6.5	10.6 ± 2.9	0.066	39.9	(.050-.910)	4.9	13.5
Left	9.4 ± 2.3	6.8 ± 3.7	0.116	42.2	(.070-.390)	2.9	8.0
Trunk Flexion Angle Right	28.6 ± 11.2	27.9 ± 9.9	0.733	16.2	(.156-.934)	5.5	15.2
Left	28.6 ± 10.6	25.7 ± 9.8	0.827	11.6	(.438-.958)	4.2	11.7
Hip Flexion Angle Right	120.4 ± 9.6	129.3 ± 15.2	0.689	5.4	(.089-.921)	7.1	19.6
Left	118.2 ± 12.6	126.3 ± 16.2	0.518	7.7	(.170-.870)	10.1	27.9
Knee Flexion Angle Right	109.4 ± 9.6	107.3 ± 7.0	0.153	4.8	(.571-.721)	7.7	21.5
Left	108.5 ± 6.3	107.6 ± 7.5	0.792	2.6	(.336-.949)	3.1	8.6
Ankle Dorsiflexion Right	55.8 ± 4.6	56.4 ± 3.3	0.162	4.8	(.644-.736)	3.7	10.2
Left	54.0 ± 5.3	54.3 ± 3.3	0.599	5.5	(.410-.961)	2.8	7.7

CI= confidence intervals, CV% = Coefficient of variance, SDD = smallest detectable difference, SEM = standard error of measurement

Table: 3.4 Between-session reliability of Single Leg Land

FRONTAL PARAMETERS	**TEST 1 (°)**	**TEST 3 (°)**	**ICC**	**CV%**	**95% (CI)**	**SEM (°)**	**SDD(°)**
Shoulder Abduction Right	17.9 ± 10.1	14.7 ± 7.9	0.881	16.5	(.336 -.975)	3.1	8.7
Left	15.3 ± 8.9	15.5 ± 13.6	0.744	30.9	(.182-.937)	5.9	16.2
Lateral Trunk Lean Right	24.7 ± 5.5	22.2 ± 11.0	0.482	23.7	(.207-.853)	6.3	17.4
Left	23.0 ± 4.2	22.1 ± 2.7	0.553	5.4	(.055-.889)	2.4	6.5
Hip Adduction Right	81.9 ± 6.8	79.6 ± 4.3	0.585	4.3	(.008-.885)	3.6	10.1
Left	86.9 ± 6.8	81.8 ± 6.7	0.505	6.6	(.230-.864)	4.7	13.1
FPPA Right	11.6 ± 4.2	12.9 ± 7.5	0.716	22.9	(.173-.927)	3.2	8.9
Left	8.6 ± 5.1	7.4 ± 3.2	0.641	23.8	(.051-.905)	2.6	7.1
SAGITTAL PARAMETERS							
Shoulder Extension Right	15.2 ± 6.9	17.0 ± 10.3	0.908	35	(.521-.982)	2.6	7.3
Left	11.0 ± 8.4	11.0 ± 5.6	0.475	31.4	(.301-.856)	5.1	14.3
Trunk Flexion Angle Right	26.2 ± 13.7	22.2 ± 11.0	0.887	13.4	(.421 -.976)	4.3	11.9
Left	25.2 ± 13.2	18.9 ± 8.6	0.696	21.1	(.058-.925)	6.1	16.9
Hip Flexion Angle Right	125.8 ± 14.7	129.3 ± 13.2	0.856	3.7	(.510 -.965)	5.2	14.5
Left	124.2 ± 16.1	129.5 ± 9.7	0.603	5.3	(.021-.891)	8.4	23.3
Knee Flexion Angle Right	110.7 ± 8.2	111.1 ± 7.5	0.871	2.1	(.528 -.970)	2.8	7.9
Left	111.0 ± 6.7	111.5 ± 10.0	0.904	1.8	(.635-.977)	2.7	7.5
Ankle Dorsiflexion Right	62.4 ± 5.3	63.0 ± 5.2	0.889	2.2	(.608-.974)	1.7	4.8
Left	62.3 ± 5.7	64.0 ± 6.9	0.789	3.7	(.354-.947)	2.9	8.0

CI= confidence intervals, CV% = Coefficient of variance, SDD = smallest detectable difference, SEM = standard error of measurement

Table 3.5 Intra-rater Reliability of Single Leg Squat

FRONTAL PARAMETERS	TEST 1 (°)	TEST 2 (°)	ICC	95% (CI)	SEM (°)	SDD (°)
Shoulder Abduction Right	9.4 ± 5.3	10.9 ± 5.2	0.932	(.458 -.988)	1.4	3.9
Left	10.2 ± 6.0	10.2 ± 6.8	0.978	(.167-.997)	0.9	2.5
Lateral Trunk Lean Right	25.7 ± 3.6	26.0 ± 3.6	0.784	(.231 -.953)	1.7	4.7
Left	24.7 ± 5.1	24.0 ± 4.9	0.977	(.829-.996)	0.9	2.4
Hip Adduction Right	81.7 ± 4.1	81.4 ± 5.5	0.731	(.016-.993)	2.5	7.0
Left	76.1 ± 7.7	77.7 ± 5.6	0.877	(.532 -.974)	2.4	6.7
FPPA Right	6.7 ± 4.7	7.8 ± 5.2	0.804	(.339-.957)	2.2	6.1
Left	5.7 ± 4.1	5.9 ± 4.0	0.988	(.946-.998)	0.4	1.1
SAGITTAL PARAMETERS						
Shoulder Extension Right	12.0 ± 6.5	11.4 ± 7.3	0.931	(.556 -.987)	1.8	5.1
Left	9.4 ± 2.3	8.6 ± 2.4	0.228	(.548-.780)	2.1	5.7
Trunk Flexion Angle Right	28.6 ± 11.2	25.5 ± 15.2	0.866	(.509-.971)	4.8	13.3
Left	28.6 ± 10.6	24.9 ± 9.7	0.883	(.280-.978)	3.5	9.8
Hip Flexion Angle Right	120.0 ± 15.9	128.9 ± 21.7	0.800	(.148-.959)	8.5	23.6
Left	118.2 ± 12.6	123.1 ± 16.7	0.866	(.401 -.973)	5.3	14.8
Knee Flexion Angle Right	109.4 ± 9.6	109.5 ± 10.0	0.921	(.654-.984)	2.8	7.7
Left	108.5 ± 6.3	105.1 ± 7.4	0.811	(.066-.963)	3.0	8.3
Ankle Dorsiflexion Right	55.8 ± 4.6	57.6 ± 5.7	0.378	(.386-.955)	4.1	11.3
Left	54.0 ± 5.3	55.0 ± 4.4	0.796	(.318-.955)	2.2	6.0

CI= confidence intervals, CV% = Coefficient of variance, SDD = smallest detectable difference, SEM = standard error of measurement

Table: 3.6 Intra-rater reliability of Single Leg Land

FRONTAL PARAMETERS	**TEST 1 (°)**	**TEST 2 (°)**	**ICC**	**95% (CI)**	**SEM (°)**	**SDD (°)**
Shoulder Abduction Right	17.9 ± 10.1	17.6 ± 10.5	0.968	(.865 -.993)	1.8	4.9
Left	15.3. ± 8.9	16.5 ± 10.4	0.882	(.583-.972)	3.4	9.3
Lateral Trunk Lean Right	24.7 ± 5.5	25.9 ± 5.4	0.974	(.896 -.994)	1.4	3.3
Left	23.0 ± 4.2	25.0 ± 5.4	0.658	(.107 -. 908)	0.3	1.5
Hip Adduction Right	81.9 ± 6.8	78.5 ± 6.0	0.795	(.026-. 957)	1.4	3.3
Left	83.2 ± 10.7	81.1 ± 6.0	0.719	(.194 -.928)	1.4	3.3
FPPA Right	11.6 ± 4.2	10.7 ± 4.6	0.917	(.657-. 981)	1.3	3.1
Left	8.6 ± 5.2	9.5 ± 5.4	0.959	(.799-. 991)	0.2	1.2
SAGITTAL PARAMETERS						
Shoulder Extension Right	15.2 ± 6.9	16.1 ± 6.6	0.961	(.833 -.991)	1.4	3.3
Left	11.0 ± 8.4	11.8 ± 8.8	0.990	(.913-.998)	3.4	5.1
Trunk Flexion Angle Right	26.2 ± 13.7	23.7 ± 11.5	0.943	(.717-.987)	1.2	3.0
Left	25.2 ± 13.2	23.9 ± 13.2	0.988	(.908-.998)	1.2	3.1
Hip Flexion Angle Right	125.8 ± 14.7	125.2 ± 14.0	0.986	(.941-.997)	1.9	3.8
Left	124.2 ± 16.1	125.1 ± 15.3	0.990	(.960 -.998)	1.9	3.8
Knee Flexion Angle Right	110.7 ± 8.2	109.5 ± 9.0	0.962	(.838-.991)	0.8	2.5
Left	110.0 ± 6.7	110.2 ± 6.6	0.984	(.861-.997)	0.9	2.6
Ankle Dorsiflexion Right	62.4 ± 5.3	61.0 ± 5.3	0.939	(.534-. 988)	1.5	3.4
Left	62.3 ± 5.7	62.5 ± 5.6	0.968	(.868-. 993)	1.1	2.9

CI= confidence intervals, CV% = Coefficient of variance, SDD = smallest detectable difference, SEM = standard error of measurement

Table: 3.7 Inter-rater reliability of Single Leg squat

FRONTAL PARAMETERS	Rater 1 (°)	Rater 2(°)	ICC	95% (CI)	SEM (°)	SDD (°)
Shoulder Abduction Right	9.4 ± 5.3	10.2± 5.5	0.823	(.568 -.901)	2.3	6.4
Left	10.2 ± 6.0	8.6 ± 7.4	0.787	(.385-.927)	3.1	8.6
Lateral Trunk Lean Right	25.7 ± 3.6	26.5 ± 1.7	0.874	(.796 -.997)	1.0	2.8
Left	24.7 ± 5.1	24.5 ± 4.5	0.957	(.437 -. 995)	1.0	2.7
Hip Adduction Right	81.7 ± 4.1	81.9 ± 6.5	0.810	(.589-. 906)	2.4	6.6
Left	76.1 ± 7.7	77.0 ± 5.0	0.812	(.342 -.899)	2.8	7.8
FPPA Right	6.7 ± 4.7	6.3 ± 4.7	0.896	(.692-. 948)	1.5	4.1
Left	5.7 ± 4.1	6.1 ± 2.3	0.998	(.806-. 998)	0.3	0.9
SAGITTAL PARAMETERS						
Shoulder Extension Right	12.0 ± 6.5	11.1 ± 7.5	0.877	(.833 -.991)	2.4	6.7
Left	9.4 ± 2.3	10.6 ± 4.1	0.696	(.913-.998)	1.8	5.0
Trunk Flexion Angle Right	28.6 ± 11.2	30.2 ± 9.8	0.945	(.717-.987)	2.4	6.5
Left	28.6 ± 10.6	30.9 ± 10.0	0.967	(.908-.998)	1.8	4.9
Hip Flexion Angle Right	120.0 ± 15.9	123 ± 17.8	0.710	(.941-.997)	9.1	25.2
Left	118.2 ± 12.6	120 ± 10.9	0.735	(.960 -.998)	6.0	16.7
Knee Flexion Angle Right	109.4 ± 9.6	110 ± 8.0	0.903	(.838-.991)	2.8	7.7
Left	108.5 ± 6.3	109 ± 7.6	0.854	(.861-.997)	2.7	7.5
Ankle Dorsiflexion Right	55.8 ± 4.6	58.2 ± 6.4	0.472	(.534-. 988)	4.1	11.2
Left	54.0 ± 5.3	53.5 ± 6.7	0.689	(.868-. 993)	3.4	9.3

CI= confidence intervals, CV% = Coefficient of variance, SDD = smallest detectable difference, SEM = standard error of measurement

Table: 3.8 Inter-rater reliability of Single Leg Land

FRONTAL PARAMETERS	Rater 1 (°)	Rater 2(°)	ICC	95% (CI)	SEM (°)	SDD (°)
Shoulder Abduction Right	17.9 ± 10.1	18.3 ± 12.6	0.935	(.797 -.940)	2.8	7.8
Left	15.3 ± 8.9	16.9 ± 9.4	0.897	(.672-.943)	2.9	8.0
Lateral Trunk Lean Right	24.7 ± 5.5	25.2 ± 6.3	0.958	(.889 -.987)	1.2	3.3
Left	23.0 ± 4.2	24.6 ± 4.7	0.951	(.893-. 985)	1.0	2.8
Hip Adduction Right	81.9 ± 6.8	84.2 ±5.0	0.799	(.364-. 847)	2.7	7.4
Left	83.2 ± 10.7	84.0 ±8.8	0.746	(.227 -.828)	4.9	13.6
FPPA Right	11.6 ± 4.2	10.8 ±4.9	0.940	(.867-. 997)	1.1	3.1
Left	8.6 ± 5.2	9.1 ±4.8	0.928	(.849-. 989)	1.3	3.7
SAGITTAL PARAMETERS						
Shoulder Extension Right	15.2 ± 6.9	16.8 ± 7.2	0.823	(.632-.945)	3.0	8.3
Left	11.0 ± 8.4	12.4 ± 8.7	0.791	(.402-.998)	3.9	10.9
Trunk Flexion Angle Right	26.2 ± 13.7	28.0 ± 15.3	0.926	(.727-.989)	3.8	10.6
Left	25.2 ± 13.2	27.1 ± 14.7	0.918	(.838-.998)	4.0	11.0
Hip Flexion Angle Right	125.8 ± 14.7	104.0 ± 20.8	0.663	(.351-.897)	10.5	29.1
Left	124.2 ± 16.1	107.0 ± 18.9	0.672	(.279-.883)	10.1	28.0
Knee Flexion Angle Right	110.7 ± 8.2	111.1 ± 7.6	0.977	(.813-.993)	1.1	3.1
Left	110.0 ± 6.7	110.8 ± 7.3	0.981	(.703-.991)	1.0	2.7
Ankle Dorsiflexion Right	62.4 ± 5.3	63.2 ± 5.0	0.944	(.453-.993)	1.3	3.5
Left	62.3 ± 5.7	63.0 ± 4.8	0.963	(.798-.988)	1.1	2.9

CI= confidence intervals, CV% = Coefficient of variance, SDD = smallest detectable difference, SEM = standard error of measurement

Table: 3.9 Within-Session Reliability of Qualitative Visual Rating Criteria QASLS

Task	**Mean**	**SD**	**ICC**	**95% CI**	**SEM**	**SDD**	**CV**
Single Leg Squat							
Right	4.78	1.79	0.82	.359-.956	0.82	1.28	37%
Left	4.78	1.86	0.86	.491-.966	0.72	1.00	40%
Single Leg Land							
Right	4.33	1.50	0.87	.423-.970	0.45	1.26	35%
Left	4.78	1.30	0.67	.025-.917	0.89	2.45	27%

Table: 3.10 Between-Session Reliability of Qualitative Visual Rating Criteria QASLS

Task	**Mean**	**SD**	**ICC**	**95% CI**	**SEM**	**SDD**	**CV%**
Single Leg Squat							
Right	4.78	1.79	0.72	.146-.929	0.96	1.65	40%
Left	4.78	1.86	0.69	.068-.922	0.99	1.75	35%
Single Leg Land							
Right	4.38	1.46	0.93	.716-.983	0.41	1.14	34%
Left	4.78	1.46	0.92	.393-989	0.47	1.52	40%

Intra-Rater Reliability of QASLS (Tables 3.11)

The within-session κ for intra-rater reliability across both single leg tasks was "almost perfect to excellent" with PEA of 100% (Table 3.11) CI (P <0.005) ranged from κ=0.85-1.0 for both tasks. Right single-leg land demonstrated κ=0.85 and 90% PEA, due to this individual component of the QASLS were further analysed.

Table: 3.11 Intra-Rater Reliability of Qualitative Visual Rating Criteria (QASLS)

Rater	**Kappa Co-efficient (95% CI)**		**Percentage of Exact Agreement (% PEA)**	
GP (1)	**RSLS**	**LSLS**	**RSLL**	**LSLL**
	1.0	1.0	100%	100%
GP (2)	**RSLS**	**LSLS**	**RSLL**	**LSLL**
	0.85 (0.73-0.98)	1.0	90%	100%

Table: 3.12 Intra-Rater Categorical Scoring QASLS Components Right Single Leg Land

	Component	Kappa (95% CI)	PEA%
1	Arm Strategy	1.0	100%
2	Trunk Alignment	1.0	100%
3	Pelvis: Loss of Plane	1.0	100%
4	Pelvis: Tilt & Rotation	1.0	100%
5	Thigh: WB Thigh	1.0	100%
6	Thigh: NWB Thigh	1.0	100%
7	Knee: Valgus(minor)	(0.68-0.92)	78%
8	Knee: Noticeable Valgus	(0.64-0.90)	78%
9	Touch Down	1.0	100%
10	Stance Leg Wobbly	1.0	100%

Intra-rater reliability has "almost perfect to excellent" agreement and 100% PEA across all categories, with the exceptions of right single leg land, items 7 and 8 were disagreed on for participants 1 and 5 respectively.

Inter-Rater Reliability of QASLS (Table 3.13)

The inter-rater reliability for all participants (Table 3.13) ranged from non-substantial (k=0.13-0.74) for single-leg squat and non-slight for single-leg land (k = 0.03-0.17). Single leg squat demonstrated the biggest discrepancy between PEA%. Rater 2 demonstrated the greatest difference between R1 and R3 (43%-90% respectively). Rater 1 was deemed the most competent rater as the creator of the QASLS model, raters 2 and 3 the novice raters demonstrated high levels of PEA with each other but low level of PEA to the specialist rater.

The inter-rater reliability for individual participants (Table 3.14) ranged from non-substantial (κ = .000-.80). Due to the lack of variance in 1 or both raters scores, kappa values could not be calculated for all raters and participants scores. The biggest discrepancy between PEA was for participant 2 on single leg squat (30-90%) whereas discrepancy between raters on single leg land was less at 10-20%.

The inter-rater reliability for categorical components (Table 3.14) was unable to be established via Kappa means due to lack of variance between 1 or both raters, even where there are high values of rater agreement (such as 100%) low Kappa scores were still noted, it is therefore likely that this data set is subject to the Kappa paradoxes where Kappa is effected by any bias between the raters or the prevalence index (the relative probability of Yes/No responses) when this is high kappa presents as low, (or the percentage of agreements observed equals the percentage of agreements expected, or the raters differ in their assessment of the frequency of the occurrence of the component in the participant group). The results may be affected by one or both of these paradoxes, however, it is difficult to distinguish between these effects. For the single-leg squat, PEA was equal to or greater than 66% for both pelvic, knee and steady stance touch down components, with less that 66% noted for arm, trunk and steady stance wobbly leg. This was different for single-leg land where PEA equal to or greater than 66% were only noted in the arm, knee position (noticeable valgus only) and touch down, all other components were graded as less than 66% by the three raters.

Table: 3.13 Inter-Rater Reliability of QASLS Criteria

Rater	Kappa (κ) (95% Confidence Interval)		Percentage of Exact Agreement PEA %	
	SLS	SLL	SLS	SLL
1 Vs 2	.125 (-0.18-0.43)	.030 (-0.30-0.63)	43.3	46.7
1 Vs 3	.182 (-0.16-0.52)	.171 (-0.18-0.52)	53.3	60.0
2 Vs 3	.737 (0.51-0.97)	.129 (-0.17-0/43)	90.0	53.3

Table: 3.14 Inter-Rater PEA and Kappa Scoring QASLS participants SLS AND SLL

Single Leg Squat						
Participant	Rater	No of Agreements	Total Tasks	PEA%	Discrepancy between PEA	Kappa (95%CI)
1	1 Vs 2	6	10	60		.310 (0.18-0.44)
1	1 Vs 3	6	10	60	20%	.200 (0.07-0.33)
1	2 Vs 3	8	10	80		.600 (0.47-0.73)
2	1 Vs 2	3	10	30		.310 (0.18-0.44)
2	1 Vs 3	4	10	40	60%	.000*
2	2 Vs 3	9	10	90		.800 (0.67-0.93)
3	1 Vs 2	9	10	90		.286 (0.16-0.42)
3	1 Vs 3	7	10	70	30%	.400 (0.27-0.53)
3	2 Vs 3	6	10	60		.800 (0.67-0.93)
Single Leg Land						
1	1 Vs 2	4	10	40		.200 (-.36-.76)
1	1 Vs 3	5	10	50	10%	.000*
1	2 Vs 3	5	10	50		.087 (-.50-.68)
2	1 Vs 2	6	10	60		.310 (-0.07-0.69)
2	1 Vs 3	8	10	80	20%	.524 (-0.05-1.0)
2	2 Vs 3	6	10	60		.310 (-0.07-0.69)
3	1 Vs 2	4	10	40		.200 (-.41-0.81)
3	1 Vs 3	5	10	50	10%	.000*
3	2 Vs 3	5	10	50		.000*

**Kappa's Unable to be calculated due to lack of variance between 1 or both raters*

Validity

There was a statistically significant moderate–strong correlation between 2D parameters and QASLS outcomes (rs_2 = .50-.83, P<0.0005) for SLS, with noticeable knee valgus weakly correlated on the left (rs = .36, P < 0.0005). There was a negative, but significant weak-moderate correlation for Hip Adduction angle during single-leg squat (rs= -.320-.624, P < 0.005) (Table 3.15).

The 2D parameters of TFA demonstrated a strong correlation to the QASLS outcome on both the right (rs = .744, p = 0.0001) and the left limb (rs = .756, P = 0.0005). Only weak-moderate correlations were observed for the other variable. There was no significant correlation noted between LTL or noticeable valgus on the left limb between 2D parameters and QASLS during SLL (Table 3.16)

ROC analysis revealed that QASLS had fair-excellent ability for all 5 variables to discriminate between those with and without LTL, TFA, Hip Adduction Angle and Knee Valgus (Table 3.17) (Figure 3.16-3.19). The area under the curve (AUC) demonstrated that QASLS significantly identified TFA and significant knee valgus (TFA = rs = .962, P = 0.0001, SKV = rs = .812-.926, p < 0.0001) during single leg land, with Hip Adduction ranging from fair-good (rs = .772-.831, P < 0.0001). The other 2 variables were poor predictors of the 2D variables (AUC ≤ 0.570) (Table 3.17) (Figures 3.16-3.23).

Table: 3.15 Spearman's Correlation (r_s), p values between 2D parameters and QASLS Score during Single Leg Tasks

Component	**SLS**		**SLL**	
	r_s value	**p-value**	**r_s value**	**p-value**
LTL Right	**.501**	**.000**	.211	.211
Left	**.444**	**.000**	-.216	.012
TFA Right	**.737**	**.000**	**.744**	**.000**
Left	**.825**	**.000**	**.756**	**.000**
HADDN Right	**-.320**	**.000**	**-.443**	**.000**
Left	**-.624**	**.000**	**-.549**	**.000**
NKV Right	**.532**	**.000**	**.375**	**.000**
Left	**.363**	**.000**	.133	.125
SKV Right	**.521**	**.000**	**.478**	**.000**
Left	**.525**	**.000**	**.308**	**.000**

HADDN= Hip Adduction Angle, LTL = Lateral Trunk Lean, NV = Noticeable Knee Valgus, SKV = Significant Knee Valgus, SLL = Single Leg Land, SLS = Single Leg Squat, TFA = Trunk Flexion Angle. Figures in bold indicate Significant correlations

Table: 3.16 Inter-Rater Categorical Scoring QASLS Components SLS & SLL

Component	Single Leg Squat						Single Leg Land					
	Rater 1 Vs 2		Rater 1 Vs 3		Rater 2 Vs 3		Rater 1 Vs 2		Rater 1 Vs 3		Rater 2 Vs 3	
	Kappa	PEA%	Kappa	PEA%	Kappa	PEA%	Kappa	PEA%	Kappa	PEA%	Kappa	PEA%
Arm Strategy	.000*	0	.000*	33	1.0[a]	100	.40 (-0.37-1.0)	66	.000*	33	.000*	66
Trunk Alignment	.000*	33	.000*	33	1.0[a]	100	.000*	33	.000*	33	.000*	100
Pelvis: Loss of plane	.000*	66	.000*	66	1.0[a]	100	.50	33	.000*	33	.000*	66
Pelvis: Tilt & Rotation	.000*	66	.000*	66	1.0[a]	100	.000*	66	.000*	33	.40 (-0.37-1.0)	66
Thigh: WB Thigh	.000*	66	.000*	66	1.0[a]	100	.000*	0	.000*	66	.000*	33
Thigh: NWB Thigh	.000*	33	.000*	66	.40 (-0.37-1.0)	66	.000*	0	.000*	66	.000*	33
Noticeable Knee Valgus	.000*	66	.000*	66	1.0[a]	100	.000*	66	.000*	100	.80*	66
Significant Knee Valgus	1.0[a]	100	.40 (-0.37-1.0)	66	.40 (-0.37-1.0)	66	.000*	66	.000*	33	.000*	0
Touch Down NWB leg	.000*	66	.000*	66	.000*	100	.000*	100	.000*	100	.000*	100
Stance Leg Wobbly	.000*	0	.000*	66	1.0[a]	100	.000*	33	.000*	66	-.80*	0

*a = 100% agreement therefore unable to provide 95%CI, * due to lack of variance between 1 or both raters unable to calculate Kappa, PEA% = Percentage of Exact Agreement*

Table: 3.17 RoC Curve Analysis for 2D Kinematics and QASLS for Single Leg Squat

Component	Repetitions SLS (n =135)		Area	Sensitivity	Specificity	1-Minus Specificity	95% CI	Angles in Degrees Cut-Off
	QASLS Yes	**QASLS No**						
Lateral Trunk Lean Right	199	200	.789	0.7	0.7	0.3	.712-.865	>24.5
Left	180	239	.758	0.9	0.5	0.5	.678-.837	>21.5
Hip ADDN Angle Right	118	301	.705	0.5	0.8	0.2	.594-.816	>79.5
Left	190	230	.861	0.8	0.8	0.2	.797-.926	>77.5
Noticeable Knee Valgus Right	248	170	.811	0.7	0.7	0.3	.741-.882	>5.5
Left	162	260	.715	0.7	0.6	0.4	.623-.806	>5.5
Significant Knee Valgus Right	44	376	.992	0.9	1.0	0.0	.977-1.0	>22.5
Left	47	373	.981	0.9	1.0	0.0	.962-1.0	>13.5
Trunk Flexion Angle Right	168	252	.934	0.9	0.9	0.1	.888-.980	>28.5
Left	187	233	.979	0.9	0.8	0.2	.960-.988	>26.5

significance set at <.05, all components had sig.000

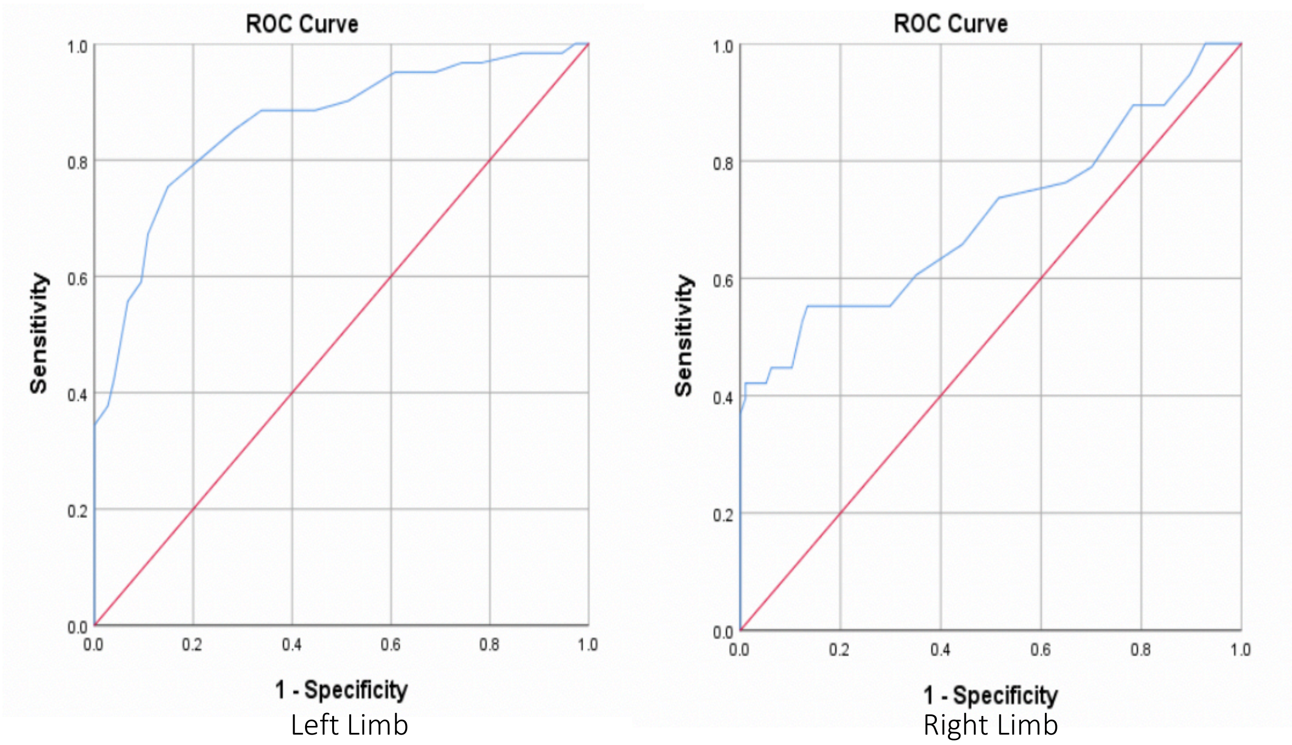


Figure: 3.15 ROC Curves Validity of 2D Components to QASLS during SLS Hip Adduction Angle

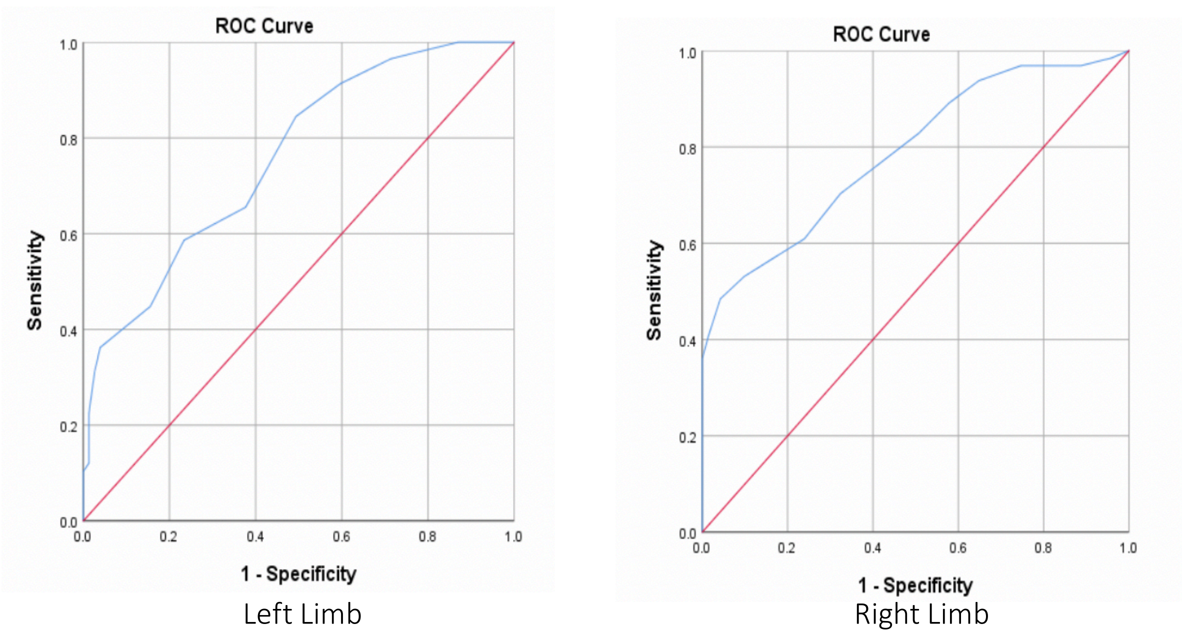
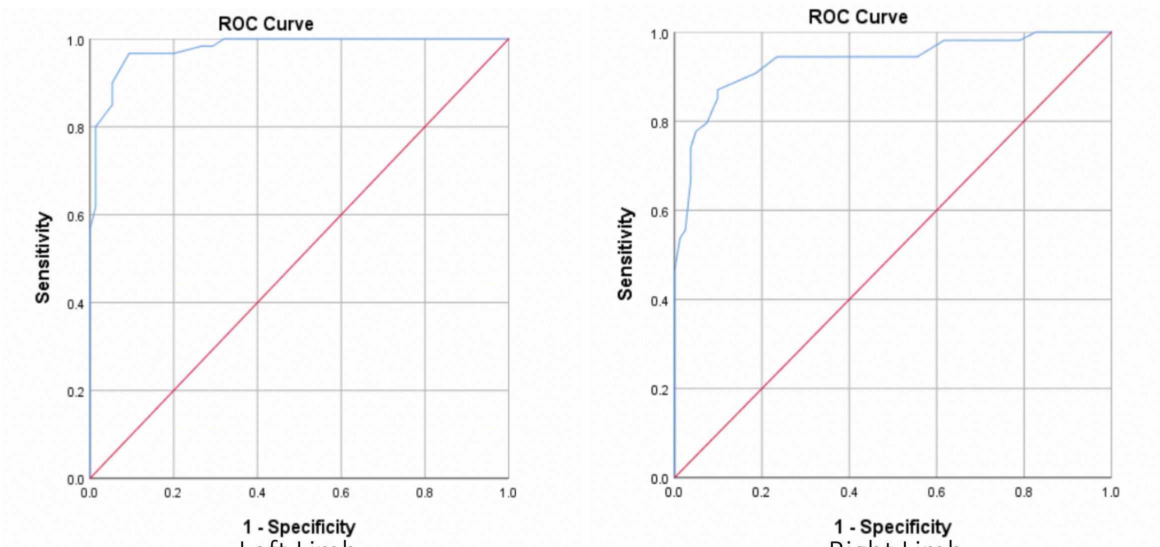
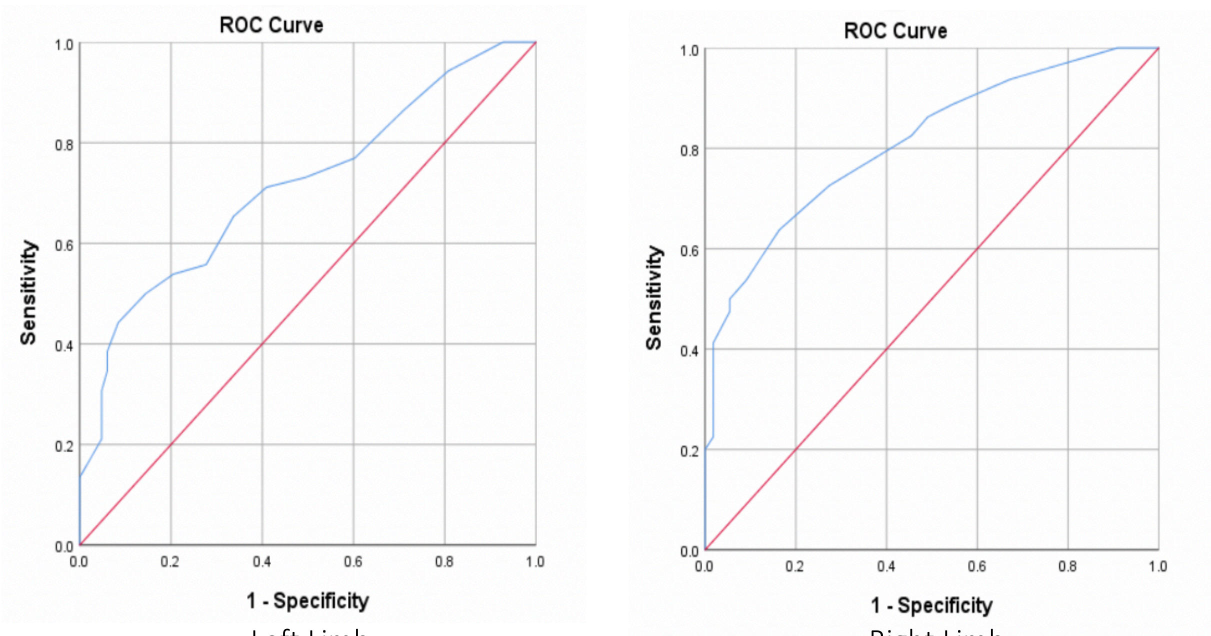


Figure: 3.16 ROC Curves Validity of 2D Components to QASLS during SLS Lateral Trunk Lean



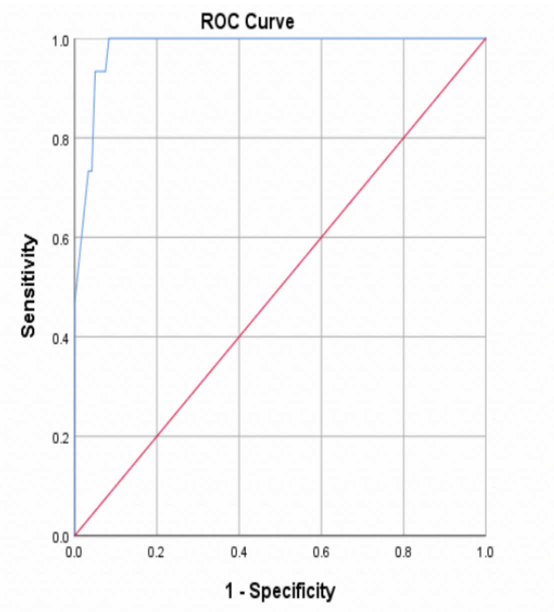
Left Limb Right Limb

Figure: 3.17 ROC Curves Validity of 2D Components to QASLS during SLS Trunk Flexion Angle

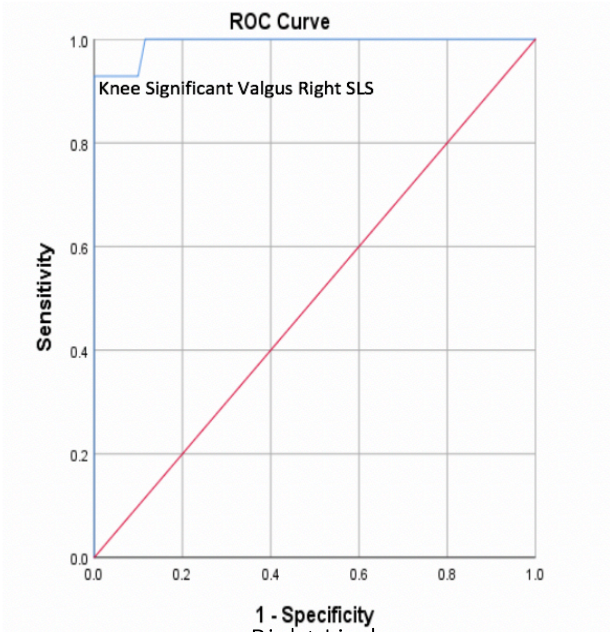


Left Limb Right Limb

Figure: 3.18 ROC Curves Validity of 2D Components to QASLS during SLS noticeable knee valgus



Left Limb



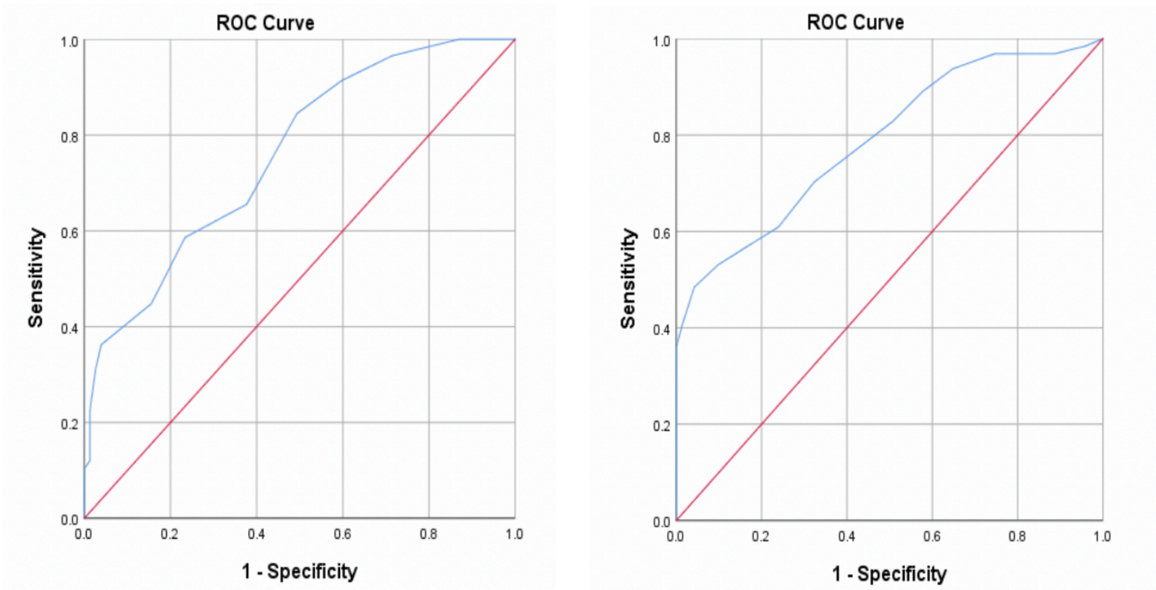
Right Limb

Figure: 3.19 ROC Curves Validity of 2D Components to QASLS during SLS significant knee valgus

Table: 3.18 ROC Curve Analysis for 2D Kinematics and QASLS for Single Leg Land

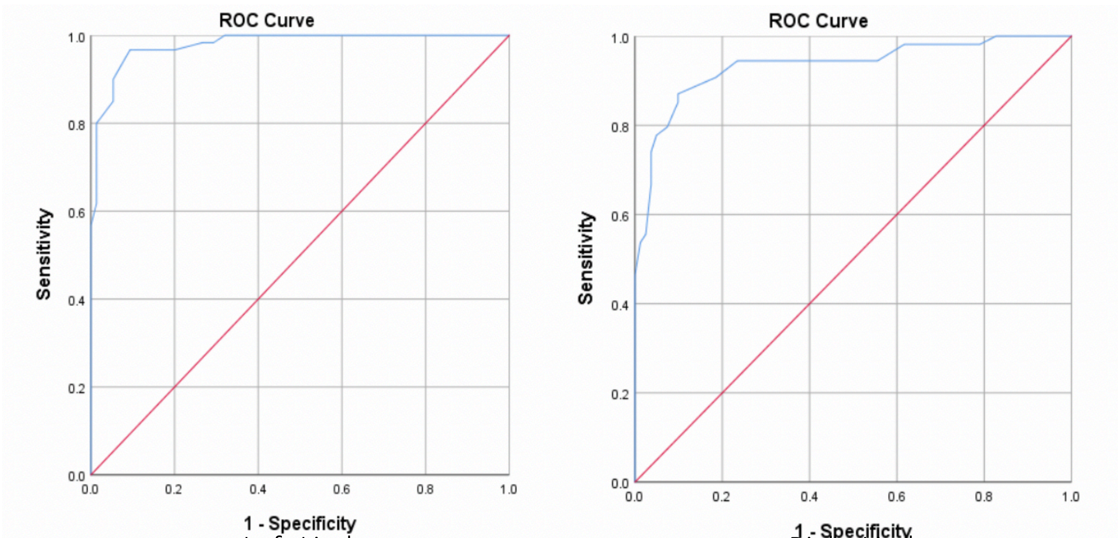
Component	Repetitions SLL (n =420)		Area	Sensitivity	Specificity	1-Minus Specificity	95% CI	Angles in Degrees Cut Off
	QASLS Yes	QASLS No						
Lateral Trunk Lean Right	126	294	.568	0.6	0.6	0.4	.466-670	23.5
Left	155	265	.372	*	*	*	N/A	N/A
Hip ADDN Angle Right	137	283	.772	0.8	0.6	0.4	.680-865	83.5
Left	150	269	.831	0.8	0.7	0.3	.756-.905	80.50
Noticeable Knee Valgus Right	280	140	.729	0.8	0.4	0.6	.642-.817	6.5
Left	269	151	.570	0.4	0.7	0.3	.471-.669	8.5
Significant Knee Valgus Right	50	369	.926	0.8	0.8	0.2	.857-.995	14.5
Left	38	382	.812	0.7	0.9	0.1	.630-.994	14.5
Trunk Flexion Angle Right	155	266	.926	0.9	0.9	0.1	.916-1.0	26.50
Left	139	281	.963	0.9	0.8	0.2	.935-.990	20.50

**area came below curve therefore no relationship, sig set at <.05 all components had sig.000*



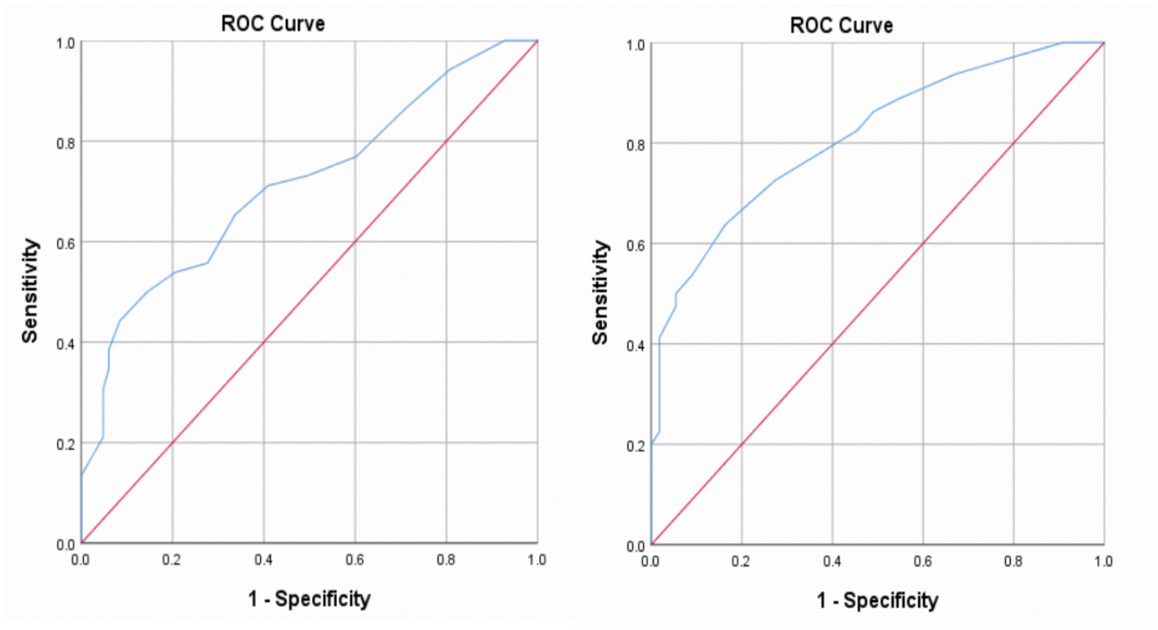
Left Limb Right Limb

Figure: 3.20 ROC Curves Validity of 2D Components to QASLS during SLL Lateral Trunk Lean



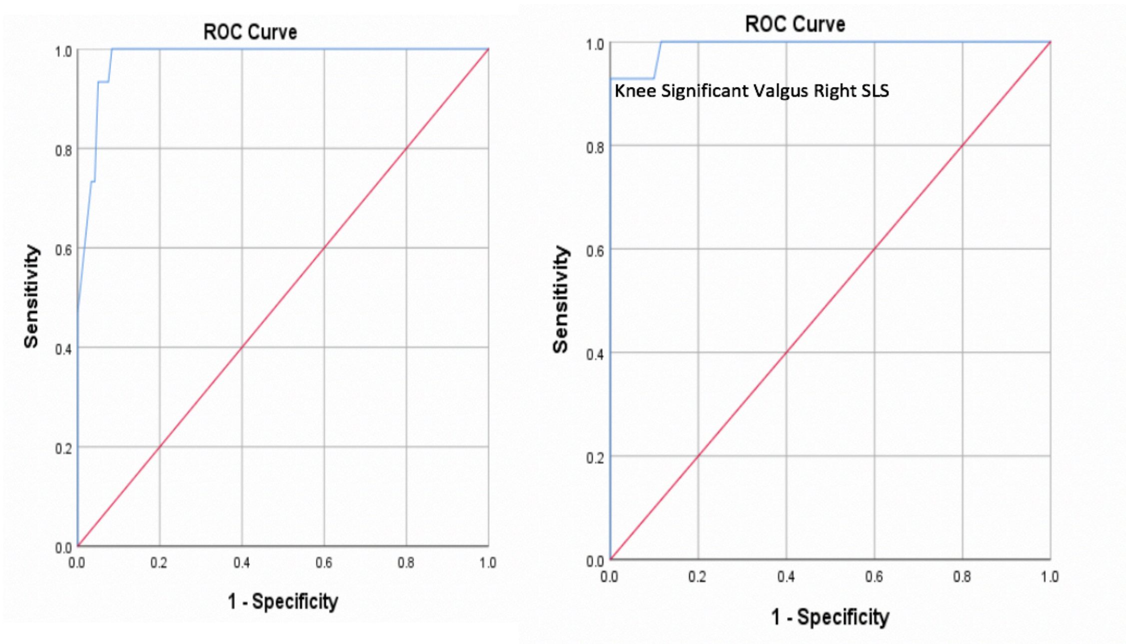
Left Limb Right Limb

Figure: 3.21 ROC Curves Validity of 2D Components to QASLS during SLL Trunk Flexion Angle



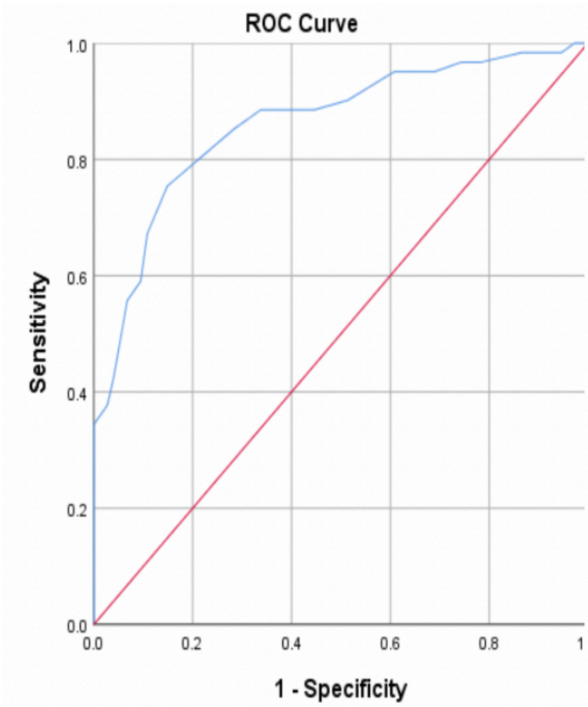
Left Limb Right Limb

Figure: 3.22 ROC Curves Validity of 2D Components to QASLS during SLL Noticeable Knee Valgus

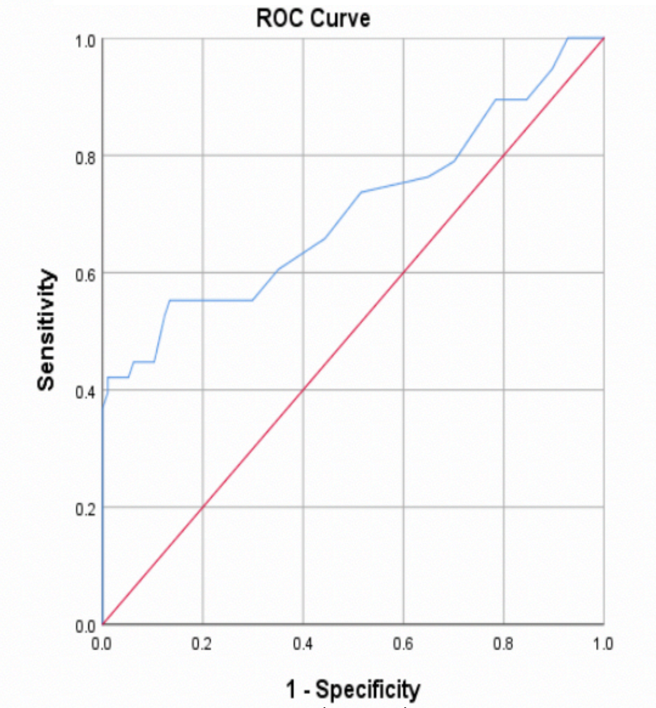


Left Limb Right Limb

Figure: 3.23 ROC Curves Validity of 2D Components to QASLS during SLL Significant Knee Valgus



Left Limb



Right Limb

Figure: 3.24 ROC Curves Validity of 2D Components to QASLS during Hip ADDN Angle

3.4 Discussion

This current study aimed where to develop and investigate the utility of a qualitative profiling tool for movement quality affiliated to the complex systems approaches identified within the literature review. By determining intra and inter-rater, and within and between-session reliability of 2D kinematic variables and the qualitative unilateral loading tool QASLS, and any associated measurement error of these methods during unilateral tasks. A secondary aim was to determine the validity of elements of the QASLS tool (components 1-10), to 2D kinematic parameters that were comparable to the body segments comprised within the QASLS components (Appendix B). The main findings are as follows: reliability for within and between sessions was moderate to excellent for both movement quality assessment methods. In contrast, inter-rater reliability for the qualitative method was less reliable than that observed in intra-rater measurements. Qualitative methods correlated with 2D measurements, whilst both were strong relationships were different between task. The QASLS tool may be considered sufficiently reliable and valid for movement analysis of the unilateral loading tasks of squatting and landing.

Previous studies that have utilised a 2D analysis approach to movement quality have been limited by the reporting of 1 or 2 variables such as DVK and or hip adduction (Willson and Davis, 2008; Munro, Herrington and Carolan, 2012). Although the inclusion of trunk capture via the frontal plane has been presented in more recent papers (Dingenen *et al.*, 2014). This conventional scientific approach of reductionism has resulted in the reduction of movement analysis from the whole-body complex movement pattern into isolated individual variables (Powers, 2010; Dingenen *et al.*, 2015; Bittencourt *et al.*, 2016). As the methods regarding movement quality analysis have simplified, conversely, the complex web of the interaction of multiple body segments, movement planes and patterns by a whole kinetic chain means movement quality itself have become more obscure. This simplicity in complexity has inadvertently prohibited the identification of multifactor injury risk.

Generally, the within-session reliability of the 2D kinematic variables was moderate to excellent for both limbs for both the single leg squat (ICC = 0.67-0.98) and single-leg land tasks (ICC = 0.66-0.98). As anticipated within-session reliability was greater than between-session reliability for the single leg squat (ICC = 0.17-0.83), whilst this was also observed during single-leg land the gap was less so. This is likely due to the nature of the landing tasks. When completing a landing task, participants are required to slow their centre of mass momentum quicker as they absorb forces into the landing phase (McNitt-Gray *et al.*, 2001; Dingenen *et al.*, 2015; Sorenson *et al.*, 2015). The strategies selected by the participants (such as erect posture, hip or knee) are likely to be more pronounced as they move outside of their base of support, and therefore easier to evaluate by a clinician during 2D analysis, which might account for the smaller variations noted during between session analysis of single-leg land. Whilst all observed SEM values were less that percentage of SDD values for both the SLS (SEM = 0.7-7.2°, %SDD = 2.3-7.9°) and SLL (SEM = 0.9-3.8°, %SDD = 2.6-5.6°), it did vary between parameters. Due to this, and the importance that observed changes in task performance are representative of true change rather than those attributed to measurement error, each 2D kinematic parameter will be discussed individually.

3.4.1 Shoulder Abduction

The within-session reliability of shoulder abduction during SLS was moderate (ICC = 0.67-0.70) for both limbs, however, this reduced to poor for between-session (ICC = 0.28-0.32). Reliability appears to be better for shoulder abduction during SLL with good to excellent reliability noted (ICC = 0.89-0.91) for within-session and moderate to good (ICC = 0.74-0.88) noted for between-session. To date no other studies, appear to have attempted to quantify shoulder abduction via 2D methods during single-leg loading tasks, therefore direct comparisons to other work are not possible. Initial results suggest that healthy female dancers will use between 8.2-13.8° of shoulder abduction during a SLS and 14-18° during a landing task. The difference observed between tasks is thought to be due to participants increase base of support on landing. Within participant variation of performance appears to be high.

Khadilkar *et al.*, (2014) has used 2D technology to quantify shoulder abduction (coronal plane) and flexion-extension (sagittal plane) during 5 different functional tasks from the Disabilities of the Arm, Shoulder and Hand (DASH) questionnaire. Though the 5 functional tasks selected were common in activities of daily living, no consideration was given to the input of the trunk or lower limb, which is in contrast to the how movement patterns were analysed within this study. Similar to the participants used in this study, Khadilkar *et al.*, (2014) presented test-retest reliability of ICC= 0.45-0.94 and SEM values of around 2-3° for the abduction and flexion/extension ranges. On first glance, shoulder abduction suggested small measurement error with ICCs associated with low SEM values (2.6-5.7°) for both limbs and tasks. However, when expressed as a percentage of SEM, comparative to the average of trial scores performance change was large (17-43%). This was also replicated in CV% where values ranged from 14.9-51.4%. Thus, despite good reliability values, overall task variability is high. With substantial variation in participant shoulder abduction movement patterns evident during unilateral loading tasks. Accordingly, if using this variable, a practitioner can expect good reliability but should expect large variations in upper limb performance, which depending on a practitioner's context may or may not impact clinical utility.

3.4.2 Shoulder Extension

Within and between-session reliability for shoulder extension was negligible to poor for both limbs during SLS (ICC = 0.07-0.19) and the left limb during SLL (ICC = 0.48-0.60). Conversely, right limb demonstrated excellent reliability (ICC = 0.90-0.91) during SLL only. Reasons for this remain unclear, but it is postulated that due to having to control frontal plane deceleration of the trunk, participants tried to create a greater base of support by using an upper limb strategy. Indeed, the range of motion noted during the trials appeared to be greater on the right limb, with participants typically demonstrating 14-17° of shoulder extension on the right compared to 10-11° on the left. Regardless of this CV% was high (12.2-42%), and similar to shoulder abduction, whilst low SEM values (2.5°) were noted when expressed as a percentage of SEM was also large (16-46%). This means that whilst clinicians should also expect great variation in shoulder extension use by participants, that is likely to be larger during SLL tasks, the 2D motion analysis approach to capture sagittal shoulder motion is not a reliable alternative to other methods of movement analysis at this time.

High CV% have been noted in both shoulder abduction and extension especially during the landing task. During gestation and the first few months of life the human body develops primitive reflexes that are a set of protective motor responses to specific stimuli (Gieysztor, Choińska and Paprocka-Borowicz, 2018). During 3-9 months the parachute reflex emerges, normally elicited when babies are placed in ventral suspension, the arms reflexively extended into flexed or abducted positions as the infant tries to catch themselves during a fall (Jaiswal and Moranka, 2017; Bennett, Lashley and Golden, 2020). Unlike other primitive reflexes that are replaced with voluntary motor activities during maturation of the central nervous system, the parachute reflex appears to persist (Jaiswal and Moranka, 2017).

There is no clear consensus as to why this is or if the reflex becomes less prominent, however it remains evident into adulthood, and is a mechanism of upper limb injury in those that fall onto an outstretched hand or wrist (Majed *et al.*, 2019). Although currently unsubstantiated, it is possible that during the landing tasks within this study the body interpreted the task as a fall and the primitive reaction from the parachute reflex elicited the employment of an arm strategy.

3.4.3 Lateral Trunk Lean

Lateral Trunk Lean demonstrated moderate to excellent reliability for within-session (ICC = 0.74-0.98) and between-session (ICC = 0.57-0.80) for SLS and SLL (ICC = 0.89-0.97, ICC = 0.75) respectively. The only exception was LTL to the right limb during SLL (ICC = 0.48) which was noted as poor. Whilst there is no directly comparable research for within or between-session reliability of lateral trunk lean, previous 3D studies (Nakagawa *et al.*, 2012) have reported trunk lean values in asymptomatic females during an SLS, and are considerably different to the values noted in this study (7.5° - 3.5° compared to 24.5-25.7°). The authors stated that female participants with PFPS presented with increased trunk flexion comparative to their asymptomatic controls and attributed the increase in trunk lean as a compensatory mechanism for hip abduction weakness.

The participants within this study demonstrated almost double the amount of mean knee flexion (107-110°) during their squats than Nakagawa *et al.*, (2012) participants, who were restricted to 60° of knee flexion. This is consistent with the concept that increased trunk lean is a compensatory strategy in order to hip and knee moments (Hewett, Torg and Boden, 2009) as participants mechanically attempt to capitalise on increased knee flexion with a larger magnitude of trunk lean. This data further highlights the potential limitations of reductionist evaluation of one kinematic variable. By focusing on the evaluation of one segmental area and limiting motion at another negates full consideration of the variable within the whole movement pattern. The differences noted in trunk lean between this work and Nakagawa *et al.*, (2012) might also be attributed to the evaluation of trunk position, in the present study trunk lean was evaluated towards the stance leg, whereas Nakagawa *et al.*, (2012) provided no clear definition as to trunk positioning through their test. Future research should look to clearly state trunk position evaluation to improve the comparison between data sets.

The results of this study show that lateral trunk lean as observed via 2D methods has better within-session consistency for both single-leg loading tasks comparative to between-session, however range of degrees noted between limbs and sessions remained consistently between 22-25°. Combined with small SEM values suggests that within this adult female population there is little variation in the strategy used at the trunk. This appears to be the first study that has delineated between session thresholds of SDD for lateral trunk lean of an asymptomatic female athletic population, with SDD values indicating that practitioners should interpret improvements of greater than 3.9-4.3° during a SLS and 4.2-6.8° during a SLL to be confident that differences in performance are present.

This study results also suggest that Lateral Trunk Lean can be measured with good – excellent (ICC = 0.78-0.98) intra-rater reliability during the SLS and moderate to excellent for SLL. Measurement error as deduced by SEM and SDD (Table 3.5-3.6) was also noted as small. Differences of smaller than 17° during SLS and 15° (within-rater) and smaller than (13°) between rater were considered non-significant. Despite consistent methods from previous research (Dingenen *et al.*, 2014), these results are slightly less than the intra-rater (ICC = 0.99-1.0) and inter-rater (0.98-0.99) values reported by these authors.

A possible explanation for the smaller ICC values shown by the adult female participants within this study could be the minimal coaching of task instruction and absence of restrictions regarding the execution of participant movement. Dingenen *et al.*, (2014) participants were restricted in squat speed and depth and given concise direct instruction to restrict head, torso, knee and upper limb position, to avoid 3D marker occlusion and compensatory arm movements. Alterations to restrict arm position effect trunk load (Olivier and Gray, 2018), increase frontal plane hip and knee kinematics in running (Agresta *et al.*, 2018) and increase trunk muscle activation (Crossley *et al.*, 2011). By selecting methodologies that restrict upper limb movements, potentially impacts trunk control subsequently reducing movement variability. This paradoxically provides greater accuracy of rater reliability measurements, but less accurate representations of inherent variable unilateral task performance. Therefore, future assessment and evaluation of lateral trunk movement quality require greater consideration around task instruction, and the trunks interaction with the whole, to maximise methodological effectualness.

3.4.4 Trunk Flexion Angle

Intra and inter-rater scores were found to be good to excellent for both SLS (ICC = 0.87 -0.88) and SLL (ICC = 0.94-0.99) as were within-session scores (ICC = 0.90-0.98) (Table 3.5-3.8). Accompanied by low SEM values (ranging from 1.2-6°) and %SDD values show that within-participant, within and between rater measurement error of TFA is small. Similar to other 2D parameters collected between-session reliability was less than within day, however, reliability remained good for SLS (ICC = 0.73-0.83) and moderate too good for SLL (ICC = 0.70-0.89).

A limitation within the trunk lean literature is the lack of evaluation of sagittal plane trunk motion. Alterations in sagittal plane trunk position effect lower limb biomechanics (Blackburn and Padua, 2008; Dingenen *et al.*, 2014; Schurr *et al.*, 2017). Participants that land with more up-right trunk postures have been shown to display increased vertical ground reaction forces as they attempt to avoid a hip strategy resulting in larger reliance on frontal plane knee movements to decelerate centre of mass (Dingenen *et al.*, 2015; Schurr *et al.*, 2017). The combination of both knee valgus and upright trunk posture has been associated with PFPS (Scholtes and Salsich, 2017) and ACL injury (Burnham *et al.*, 2016). Therefore, the evaluation of trunk flexion via the sagittal plane is an important component for clinicians when evaluating risk factors and movement quality. The results of this study indicated that analysis of 2D sagittal trunk flexion angle can be reliably collected with small amounts of measurement error and that clinicians should be looking for changes in at least 6-7° of trunk lean to justify notable changes in performance in adult females.

3.4.5 Hip Adduction Angle

Despite slight differences between tasks, 2D analysis of hip adduction was shown to be reliable during both single-leg movements. Within session reliability of the SLS (ICC=0.78-0.94) was slightly better than previously reported values (Munro, Herrington and Carolan, 2012; Herrington *et al.*, 2017), with SEM values (SEM = 1.3-3.1°) appearing to coincide with those previously reported in university-age participants (Munro, Herrington and Carolan, 2012; Herrington *et al.*, 2017; Gwynne and Curran, 2018).

However, in contrast to previous SLL work (Munro, Herrington and Carolan, 2012; Herrington *et al.*, 2017) between-session reliability in this study was substantially less, with larger confidence intervals (Table 3.4), despite no significant difference in mean scores.

Within this study, results are reported as an average of 5 trials and each individual limb. In spite of both limbs being tested and analysed separately, Herrington *et al.*, (2017) reported results as a combination of both independent limbs and reported results as an average of 3 trials. The current study does not support result reporting in this way and suggests that combination reporting limits the availability to compare limbs within and between subjects and at different points in time.

Although this study has reported each limb individually, limbs have not been classified by dominance. Concerning this potential limitation, unlike other sports where dominance is usually decided by the generic task of kicking a ball, within dance no limb is considered particularly dominant. There may also be situations where over-focus on the dominant limb leads to the missed evaluation of the none dominant limb. For example, during sporting movement patterns the dominant limb may be overburdened and exposed to more load, whereas a non-dominant limb maybe under burdened and less tolerable of load (Gwynne and Curran, 2014). It is therefore argued that regardless of dominance both limbs are at risk of injury, all be it by potentially different causes, and should therefore be evaluated separately.

Studies analysing inter-rater reliability of hip adduction during unilateral loading tasks have reported similar results to those documented in this study (Table 3.7-3.8). There appears to be no reported data on intra-rater values specifically for single-leg squatting or landing. The moderate to good reliability (ICC = 0.73-0.88) of hip adduction during both unilateral tasks found in this study is cognisant with 2D analysis of hip adduction during complex unilateral movement such as running (Maykut *et al.*, 2015). Overall hip adduction appears to be a consistent measurement tool for use by the same rater and provides practitioners with a practical, feasible and accessible metric to analyse lower limb strategies during unilateral loading tasks.

3.4.6 Hip Flexion Angles

Good to excellent within-session reliability (ICC = 0.76-0.96) has been demonstrated for both landing tasks, however, between-session reliability was less reliable with SLS fairing as moderate (ICC = 0.52-0.69) and SLL moderate to good (ICC = 0.60-0.86). Within-day SEM suggests that >7.2° and > 3.8° of hip flexion are required to demonstrate differences in the SLS and SLL respectively, which increases to >10° and >8.1° for between-session changes during both loading tasks. Due to the required changes in %SDD being large to ensure performance changes are not due to statistical effect clinicians cannot be confident that associated changes in performance are not attributed to the measurement error. Intra-rater reliability was demonstrated differences for each task, with SLL producing excellent reliability (ICC = 0.99), and SLS showing moderate levels of reliability. SEM values were 1.9° and %SDD 3.8°.

Similar to the within and between session data performances changes that are beyond measurement error would have to be vast (Tables 3.5-3.6). Results show that despite acceptable levels of reliability, due to discrepancies in measurement error and the minimal changes required to ensure statistical significance, the use of 2D motion to capture hip flexion angle during two single-leg loading tasks is not supported. Comparative to frontal plane analysis, substantially less research has been conducted into the sagittal plane evaluation of dynamic movement patterns, and there are no published articles with SLL and SLS to provide direct comparisons. Two papers have analysed the validity of 2D sagittal plane angles via comparison to goniometry (Gribble *et al.*, 2005; Norris and Olson, 2011). Whilst neither set of authors specifically analysed unilateral loading movements, (Gribble *et al.*, 2005) analysed hip flexion angles during SEBT which requires participants to perform a single leg squat movement and Norris and Olson,(2011) analysed hip flexion via 2D through a mechanical lifting squat that required deeper angles that might be more representative of a single leg land. The reliability values within this study are consistent with those reported within the above literature, but SEM values are much smaller (0.75-2°). The observed differences in SEM values is potentially due to the greater movement variability noted in this study and is further evidenced in large confidence intervals.

As seen during the investigation of other 2D kinematic variables within this work, differences in the reported measurement error in this study are potentially connected to the methodological approach of allowing participants to squat to an unrestricted depth. Participants within Gribble *et al.*, (2005) study were limited to designated angles with the hip being restricted to 45°, the nominated angle was recommended as a delimiter to the usage of goniometry measurements which are unable to account for the accessory spine and trunk motion that can occur at greater hip flexion depth. Participants hip flexion angles within this study were observed as being much greater at 118-130°, as a result, greater variation was noted within these studies, this could be due to these individuals using other segmental strategies that participants with restricted ranges did not use. Norris and Olson, (2011) found similar results with hip flexion when using self-selected depth position during their lifting task (115°± 11.2°) although standard deviation (SD) was smaller due to the bilateral nature of the squat which required less proprioception and neuromuscular control than the unilateral tasks within this study. This would result in less variation in movement and could account for the improved reliability.

2D analysis is limited in its ability to measure rotation (DiCesare *et al.*, 2014) Frontal plane values can be altered due to combined effects of rotation at the knee and hip and it is not, therefore, unreasonable to postulate that similar rotations of the pelvis and trunk affect analysis within the sagittal plane. Moderate inter-rater agreement (κ= 0.55) has been shown via 3D motion analysis during SLS tasks with hip flexion restricted to 45-50° (Barker-Davies *et al.*, 2018; Mostaed, Werner and Barrios, 2018). Even in highly controlled tests that use the gold standard 3D method of motion analysis and inadvertently control for movement variability by restricting movement depth, rater-agreement of sagittal hip range evaluation has only been shown to be statistically “moderate” (McLean, Huang and van den Bogert, 2005). This implies that rater reliability would occur at best 55% of the time in a controlled laboratory environment through a controlled movement range. It would not be unreasonable to presume that as movement variation increased, rater-reliability would decrease accordingly. In term of practical application, rater-levels of < 55% agreement are potentially unacceptable, especially within the context of elite sporting performance.

2D Sagittal plane hip angles during a single leg squat have been found to be reliable through R-values (r = 0.99, 95% CI: 0.98-0.99) when compared to 3D movement capture (Schurr *et al.*, 2017). However, 2D and 3D agreement was established against goniometry measurements reported by other authors in different studies, which questions the substantiation of these findings. Due to the complexity of pelvic combined movement, it appears that evaluation of all for forms of motion analysis of sagittal hip flexion angles still has far to go, and should be investigated further as part of the non-linear cause-effect relationship of movement pattern analysis.

3.4.7 FPPA

Statistics for between and within-session 2D FPPA are presented in tables 3.1 and 3.3 for SLS and tables 3.2 and 3.4 for SLL. 2D FPPA measures demonstrated excellent within-session (ICC = 0.91-0.93) and moderate to good (ICC = 0.65-0.79) reliability for SLS and moderate to good (ICC = 0.64-0.86) for SLL on both occasions. SEM values ranged from 1-3° (Tables 3.1-3.4). This is consistent with other authors who have reported between session ICC that range from ICC = 0.72-0.74 (Munro, Herrington and Carolan, 2012; Gwynne and Curran, 2014) and 0.87 (Herrington *et al.*, 2017) for SLS and 0.82 – 0.87 for SLL (Munro, Herrington and Carolan, 2012; Herrington *et al.*, 2017). The slightly higher within-session reliability (ICC = 0.91 -0.93) found in this study compared to other reported values of 0.59 – 0.86 (Munro, Herrington and Carolan, 2012; Gwynne and Curran, 2014) is likely to be due to the participants selected. Both the above authors drew participants from the recreationally active university population, due to the intensive training within this population there is likely to be less within-participant performance variation through the SLS task and could account for greater ICC values noted here. SEM values found within this study are also comparable to those presented in other studies (Munro, Herrington and Carolan, 2012; Gwynne and Curran, 2014; Herrington *et al.*, 2017). ICCs reveal that 2D FPPA has good test-retest reliability between participants and sessions and that 1-4° remains an acceptable amount of clinical error, and that FPPA remains a reliable and accessible tool for clinicians.

The intra and inter-rater reliability results (ICC = 0.80-0.99) and associated small measurement error (0.2-3.2°) continue to follow those in other published work (Ageberg *et al.*, 2010; Kennedy, Burrows and Parent, 2010; Poulsen and James, 2011; Gwynne and Curran, 2014; Herrington *et al.*, 2017), and further support the continued use of 2D FPPA as a good alternative to 3D motion analysis between raters. Whilst it is acknowledged that 2D FPPA continues to be a viable alternative for clinicians within an elite athletic group, this athletic population were of similar ages to the university participants used in Munro, Herrington and Carolan, (2012) and Gwynne and Curran,(2014) studies, future recommendations are made to complete additional work on other age groups such as adolescents and in different sports where physical qualities of movement quality may be different.

3.4.8 Knee Flexion Angle

Reliability values of sagittal plane knee flexion angles are presented in tables 3.1-3.8, with the overall reliability of this 2D measure being shown to have excellent intra, inter and test-retest reliability. As with hip flexion angles, the majority of the l2D motion analysis literature focuses on the knee from the frontal plane. However, the results of this study appear to be in line with the small number of studies that have analysed the knee from a sagittal aspect during bilateral squatting (Norris and Olson, 2011; Ross *et al.*, 2015) and walking (Ameer, 2016).

Reliability was different between tasks, with SLS demonstrating good to excellent reliability (ICC=0.81-0.97) and SLL demonstrating (ICC=0.84-0.96). Caution for this variable must be advised as measurement error for the right limb was almost equivocal to the level required for actual performance change (SEM = 7.6°, %SDD = 7.7°). Due to the previous lack of research, it is difficult to make comparisons with this study’s findings or provide a conclusive explanation for the reliability differences observed between tasks, especially when there is no statistical differences or uneven distributions reported within the data set.

Increased knee flexion is usually associated with increased hip flexion (Blackburn and Padua, 2008), with increased knee flexion angles also shown as being related to increased hip flexion moments (Dingenen *et al.*, 2014). The participants in this study also demonstrated poorer between-session reliability of SLS hip flexion angles, due to aesthetic requirements, dance is traditionally performed with a more upright trunk position and as a result a more erect landing pattern. The data of both the sagittal 2D hip and knee variables within this study suggests that the participants had a variety of whole kinetic chain movement strategies to perform SLS tasks, and infers that elite trained populations may employ different movement strategies on different occasions as they have an extensive repertoire of movement patterns available to them. Previous work (Dingenen *et al.*, 2014) on participants from the same sporting groups and supposedly same sporting movement patterns showed the adoption of a mixture of both erect and knee dominant loading patterns. Based on the results of this study sagittal plane knee flexion angles appear to be reliable for within and between-raters for SLL tasks, but further work is needed to establish if reliability differences exist within different athletic and age groups over different time points for the SLS task.

3.4.9 Ankle Dorsiflexion

Intra and inter-rater reliability of sagittal plane ankle dorsiflexion during SLL were excellent (ICC = 0.94-0.97) within and between-session reliability demonstrated good reliability (ICC = 0.79-0.89). SEM values were also noted as low (1.1-2.9°), with %SDD being highest for between session ankle dorsiflexion for the left limb (4.7°). The results show that ankle dorsiflexion observed from the sagittal plane is a reliable 2D measure and that during landing, changes of approximately 5° demonstrate a truly meaningful change.

Surprisingly the same reliability was not demonstrated during the SLS. Within-session reliability was good (ICC =0.88-0.89) between-session reliability was poor for the right limb (ICC = 0.16) and moderate for the left limb (ICC = 0.60). This was reflected within, intra-rater reliability which demonstrated poor (ICC = 0.38) reliability for the right limb, good reliability for the left limb (ICC = 0.80). Measurement error (whist still within acceptable boundaries) was also slightly higher during the SLS with SEM of 1.5-3.9° being reported. Within-session reliability off sagittal ankle range has been reliably reported at midstance (ICC = 0.80) during gait (Ross *et al.*, 2015). The bulk of the literature reports relationships, associations and correlations of DF angle to the knee and hip sagittal kinematics (Mason-Mackay, Whatman and Reid, 2017), rather than measures of reliability. Therefore, direct comparisons to unilateral loading tasks are difficult. As evidenced in other sagittal parameters (see sections 3.4.7 and 3.4.8) concerning the knee in this study. The difference in between -session reliability at the ankle potentially further supports the "coordinative ability" concept (Hamill, Gruber and Derrick, 2014) that individuals, especially elite trained ones like the participants in this study can deploy numerous patterns for the same task on different occasions. Leading to less reliable within-session results. This study recommends the use of 2D ankle dorsiflexion parameters for unilateral landing tasks but urges caution with its interpretation during squatting tasks.

All in all, the nine 2D kinematic parameters investigated within this study have provided extensive differences in rater and participant reliability during both unilateral tasks, demonstrating large variability of movement overall parameters. The participants within this study appear to use multiple strategies, but ins some instances too few participants select the same one for mean differences to be statistically recognised. Although results may be statistically non-significant it does not mean that movement changes are not occurring. The collective findings of the 2D variables demonstrate that participants change the combinations of the way they use multiple parameters which are unable to be detected by analysis of a single parameter, further highlighting the potential restrictions of 2D analysis if variables are only viewed in isolation.

Very few studies investigate more than one 2D variable (with 2 being selected at most), which adds to the confounding between-session reliability results and the limitation of identification of interactions within movement patterns that would not be evident in the individual analysis of the 2D variable alone. Investigation of 2D movement analysis continues to be important as a more accessible means of motion capture. The limitations and restrictions demonstrated in the scientific reductionist approach of singular 2D variable analysis, further highlight the need for easier, accessible measures that remain sympathetic to the orthodox analysis of results ensuring that practitioners have a system that is reliable and sensitive to performance changes. Qualitative analysis may bridge that gap, allowing for analysis of individual segmental pattern changes, but within the context of the whole kinetic chain, allowing observation of the interaction of those individual segments within the whole complex movement pattern system.

3.4.10 Reliability of QASLS

A second objective was to assess the within-session and between-session reliability of QASLS and to compare intra and inter-rater scorings of the two unilateral loading tasks. The moderate – good reliability results for both within and between sessions (ICC = 0.67 -0.87 and 0.69-0.93 respectively) indicate that compound scoring from QASLS tool is reliable within participants and on different occasions. Results also highlighted that there was a measurement error of 1 between timeframes and that a change of 1-3 points would be required to determine a change in performance. Only two studies (Almangoush, Herrington and Jones, 2014; Herrington and Munro, 2014) have so far analysed reliability elements of the QASLS tool but these have been limited to intra–inter-rater and validation. This is believed to be the first study to provide test-retest reliability specifically for QASLS tool.

Other available qualitative movement screens that use dichotomous scales similar to QASLS such as the FMS and LESS have reported ICC values of test-retest reliability that are similar to the results reported here. Shultz *et al.*, (2013) establishing that compound FMS scoring was relatively good (ICC = 0.6) for elite female athletes when tested 7 days apart. A systematic review stated that despite ICCs being commonly reported in reliability studies, within qualitative research many interpretations of the ICC exist and therefore clarification of excellent or good reliability is elusive with studies classifying values > 0.75, > 0.80 and 0.40-0.75 as excellent or fair to good (McCunn *et al.*, 2017).

Even though the QASLS tool appears to be a reliable instrument for within and between-session reliability, caution should be applied to the automatic application to other populations. Future research investigating test-retest reliability is also required in different sporting and age populations.

Intra-rater reliability within this study was excellent (PEA = 0.90-1.0 and kappa coefficients ranging from κ = 0.85-1.0) and in agreement with another study (Almangoush, Herrington and Jones, 2014) that specifically used the QASLS tool and 4 different raters to analyse the

SLS. In the present study, the 3 raters demonstrated significant differences in components 7 and 8 (regarding knee valgus) (figure 3.15) of the QASLS tool. Previous findings (Almangoush, Herrington and Jones, 2014) also concluded rater disagreement during the scoring of SLS in male and female university participants. The raters in this research, as with the raters in this current study received no formal training and were reliant on the operational differences presented within the tool. The operational differences presented in components 7 and 8 of the QASLS tool are very similar in their description, which might not be concise enough for raters to deduce the difference between the terms "noticeable" and "significant". It is therefore unclear if the reliability results observed in this study are attributed to the level of rater training or vagueness of the operation definition of knee valgus. This might also provide an explanation for why these differences were not reflected in SLL results where the greater complexity of the task suggests that valgus is easier to spot within this movement pattern. Inter-rater compound scoring reliability of multiple participants was none-substantial for SLS with PEA was 43-90% and κ = 0.03-0.17), this is substantially lower than previously reported (Almangoush, Herrington and Jones, 2014). These results were compared with other papers that have analysed SLS via other qualitative measures. Chmielewski *et al.*, (2007) showed PEA of 32-48% during SLS via segmental approach and weighted kappa values of κw 0.00-0.53 (Shultz, Scott C Anderson, *et al.*, 2013) described inter-rater agreement via Krippendorff α ($\kappa\alpha$) as poor ($\kappa\alpha$ = .38) when using the FMS on female athletes. Whilst the methodological design of the studies inhibits direct comparison to the results from the study, it does illustrate the progression of the method of qualitative motion analysis via visual rating criteria.

A better agreement was noted when raters scores were considered for individual participant scoring rather than across whole group scoring. Both PEA and κ values (that determine agreement not attributed to pure chance)(McHugh, 2012), were generally higher for analysis of raters for each participant. In addition, a discrepancy between PEA was included (or the difference between raters for each participant) into results (Table 3.14) which indicated that the difference between the 3 raters scores for within-participant was between 20-60% for SLS and 10-20% for SLL. Although this approach is limited in statistical robustness, whether a 10-20% difference in rater measurement is deemed acceptable within real-world application remains to be seen.

Categorical scoring of each component of the QASLS also leads to mixed inter-rater reliability with fair – almost perfect agreement (κ = 0.40-1.0). The best scores appeared to be between raters 2 and 3 for SLS where raters were in 100% agreement in 8/10 categories with, disagreement around components 6 and 8 (NWB thigh movement and noticeable knee valgus). Inter-rater reliability was unable to be calculated for a lot of categorical components, due to lack of variance between 1 or both raters, this was particularly noticeable with rater 1 the specialist rater, and is potentially attributable to the kappa paradoxes. When compiling this study, a couple of important decisions had to be made, due to previously minimal research around the QASLS tool, the first decision was around how to treat the variable generated by the QASLS method as this would dictate the statistical approach. 2D data is numerical in nature following interval or ration principals, and are therefore quantity variables that can be parametrically analysed. The case could be made for QASLS being classified as ordinal (due to the dichotomous element to the segmental evaluation where the outcome falls into 2 categories of yes or no) and interval (compound scores that run on a scale of 0-10 where the gaps are proportional), this and how best to establish how the tool performs in relating to reliability and agreement was open to debate. As the tool was initially designed as a clinical instrument to guide practitioners in high-risk single leg loading patterns of the whole system providing a total compound score, not as a predictor of injury, and due to other visual rating methods, that also use dichotomous scoring treating their data as interval (Padua *et al.*, 2009, 2011; Crossley *et al.*, 2011; Whatman, Hume and Hing, 2013), the decision was made to evaluate data as an interval variable. Data analysis limitations is discussed further in section 3.4.12.

Overall the qualitative QASLS tool has demonstrated satisfactory intra-rater and within and between-session reliability for its use by practitioners. Further work on inter-rater education would be beneficial before the tool is used amongst the wider-spread clinical population.

3.4.11 Validity

Statistically significant correlations were found for all 5 components between 2D variables and QASLS categories for SLS, and TFA, HADD for SLL with valgus also being significantly correlated for right limb during SLL only. These conclusions support the only paper

(Herrington and Munro, 2014) that has attempted to validate any aspect of the QASLS tool, which demonstrated strong validity of QASLS to represent accurate 3D motion capture. Although no comparison of QASLS to 2D was made, Padua *et al.*, (2009) demonstrated strong validity to 2D and 3D analysis when using a different visual rating criterion (LESS), and Dingenen et al. (2014) also showed significant correlation of 2D against 3D of Knee Valgus to lateral trunk motion during a single-leg vertical drop jump. The authors (Herrington and Munro, 2014) attempted to reduce 3D kinematic data to dichotomous scores based on normative values from other researchers. Whilst this study has emulated this method by substituting 3D forms of capture with 2D methods, it has gone 1 step further by using double the number of participants and attempting to establish sensitivity and specificity around movement segments of the tool.

The receiver operating characteristic (RoC) and the area under the curve (AUC) provided summary validity measures for each component and limb. When determining sensitivity and specificity each value should be as high as possible, with as low as possible false-positive rates, depending on if sensitivity (the ability of the tool to correctly identify those with the movement error) or specificity (the ability of the tool to correctly identify those without the movement error) (Sedgwick, 2015) is more desirable. This is determined upon the practical significance of identifying those with the movement error in relation to a sport or injury (e.g. increased trunk lean is desired in some sports but considered detrimental in others, therefore, identifying those with might be paramount). Due to the requirements of establishing the value of QASLS tool in identifying movement quality relative to quantitive measures, it was decided that the sensitivity of the tool for identifying participants with the movement error was more important, and therefore tests with high specificity has reduced false negatives and more likely to identify participants with that error.

Cut off values closest to the left top corner of the RoC Curve (Figures 3.18 and 3.19) were selected, as by prioritising sensitivity over specificity where possible, within the context of movement screening and profiling, ensures that participants with false-positive results (identified as having movement error but actually don't) and false negatives (identified as not having movement error but actually does) are less likely to be excluded from any intervention programme clinicians may provide to address associated risks affiliated with movement quality. Cut off scores are detailed in table 3.18 for SLS and table 3.19 for SLL, with recorded degrees of motion fairly similar between most tasks (e.g. Hip Adduction angles 77-80°). In this work, various 2D variables were tested as part of identifying comparators for validating the QASLS tool, as validity cannot be proven without firstly establishing reliability. Even though numerous variables were tested from both the sagittal and frontal plane to try to replicate a more multiplanar view that is possible with qualitative analysis, only those regarding trunk lean, hip adduction and knee valgus could be taken forward, information around the ankle and upper limb concerning QASLS are yet to be validated via 2D methods. The fair to almost perfect validity of QASLS for the trunk, hip adduction and valgus components during the SLS constitute the need for additional research to distinguish between those who display these errors and how that interplays with movement quality and injury risk factors.

3.4.12 Strengths and limitations

One of this study's strengths is the evaluation of unilateral movement patterns in a way that has not previously been extensively considered. It appears that no previous work has analysed both frontal and sagittal parameters from a 2D perspective as part of a wider movement pattern. Similarly, it has added to the smaller body of research concerning the qualitative assessment of whole movement patterns. It is felt to be a useful addition to the literature to determine how previously evaluated singular variables of movement may be considered and incorporated into a more complex systems approach. Furthering methods of movement quality assessment, by advancing the reductionist approach in a non-linear fashion that hopefully better identifies relationships of potential injury risk determinants.

There are some inherent limitations within the study that require consideration when interpreting the study's findings. Firstly, inter-rater reliability for the qualitative method needs to be improved before recommendation for widespread multicentre use is supported.

de Vet *et al.*, (2006) describes reliability coefficients "as the information providers on the ability of test scores to distinguish between participants and test occasion," and as such the ICC method was the most appropriate method for determining within and between-session reliability for the compound QASLS scoring (Hernaez, 2015; Koo and Li, 2016). Unlike intra-rater and test-retest reliability, inter-rater reliability is not as straightforward (Morris *et al.*, 2008; Koo and Li, 2016). According to McGraw and Wong, (1996), correct selection of ICC for interrater reliability requires the satisfactorily meeting of 4 presumptions regarding model, type and definition. To satisfy the assumptions of a two-way random effects model, it is presumed that the selected raters will have the same characteristics (e.g. years of experience). Although representative of the larger practitioner population, due to the newness of the QASLS tool it is unlikely raters displayed the same clinical and experience characteristics and therefore the satisfaction of the two-way random-effects model was questionable. Whilst the two-way mixed-effects model would have addressed this limitation, results would only apply to the selected raters within this study, and could not have been generalised to the wider population. Therefore, other statistical methods were sought.

There are several statistics available to measure inter-rater reliability. Due to applicability and standardisations to both categorical and numerical data percentage of exact agreement (PEA) and Cohens Kappa (κ) are the advocated statistics(Morris *et al.*, 2008; McHugh, 2012; Hernaez, 2015). A strength of this study was the presence of both methods, however, neither method is without fault. PEA is a precisely, interpretable and easily determined statistic but does not account for chance rater guesses (McHugh, 2012), the kappa value eliminates any chance rater choices, but is limited in sensitivity to "true" prevalence within data, where estimate agreement is excessively lowered in homogenous populations or data prevalence that clusters very high or very low (Hernaez, 2015).

This is usually seen in a moderate to high PEA and a low κ score and is frequently described as the "base rate problem" (Morris *et al.*, 2008). This has been shown in very simple cases with only 2 evaluators and 2 outcomes (similar to this design) with the paradox occurring at equal points of the sensitivity and specificity of the raters, or if the prevalence of 1 of the raters is above 60% (Zec *et al.*, 2017) as frequently observed between raters 1 and 2, and 1 and 3. The population within this study are likely to be well drilled in patterns of movement, it is expected that dancers would be able to execute the same movements repeatedly. Data indicated that at the individual level, movement variability was high with different movement patterns were deployed within the same movement pattern, but as an overall cohort movement patterns were consistent and therefore variability was low.

It is unsurprising that this data set has high levels of homogeneity that is likely unavoidable in the analysis of an elite population. The analysis of movement quality is a key aspect of profiling and programming within the sporting environment, it is therefore likely that future research will continue to be focused within this population. It is prudent to acknowledge the limitations of this non-heterogeneous sample and the likely impact that would have on a kappa score, a truly heterogeneous elite sporting population would be difficult to achieve. The argument is therefore made that the limitation is within the statistic rather than the direct relevance of the population. Continued research into other sporting populations such as younger children and adolescents where a cohort could be relatively heterogeneous in their construct would be warranted.

There were high levels of the same ratings across some of the categorical components of the QASLS tool, data variance was slight and kappa values were accordingly low, this was regardless of high to perfect 100% observed PEA (Tables 3.15 and 3.17). If raw κ scores alone were just accepted within this study, then the acceptance of none too fair inter-rater reliability for categorical aspects of the QASLS scores and the compound score would have to be acknowledged, when this might not actually be the reality. When it comes to PEA there is no universally applied definition on what classes as good or excellent or even poor with values as low as 50% to as high as 90% being proposed as cut off values within the literature. Stemler (2004) advising that cut off values of PEA should be decided within the context of each study whilst 50% agreement might not be acceptable in certain contexts it most certainly would in others. Based on this a PEA of > 66% was deemed acceptable within this cohort.

A final limitation of the study is the level of rater training provided in using the QASLS tool. The findings of the kappa results are potentially suggestive of a redesign of the test instrument or retraining of the raters (McHugh, 2012). Given the robustness of the intra-rater and between and within-session results, the requirement for full instrument redesign appears unlikely. However, there is scope to impact rater-training. All raters were provided with the same standardised instructions on how to administer the tool and there are basic operational definitions embedded within the tool next to each component segment. It is possible that each rater interpreted each section in a specific way which ultimately impacted agreement.

Whilst training around the using and interpretations of other movement visual rating criteria is standardised by other authors, it was decided that understanding the current interpretations, limitations and strengths of the QASLS tool as it stands currently within clinical practise, was more pertinent. Results demonstrate that the current operational definitions within the tool are suboptimal for multi-rater use but adequate for intra-rater use.

Rater training is an important component to qualitative analysis (Minick *et al.*, 2010) but rarely appears to be delivered in a standardised way. Researchers have provided basic verbal instructions in the visual analysis (Shultz, *et al.*, 2013) open discussion with other raters to resolve confusion around rating guidelines (Chmielewski *et al.*, 2007), selected raters with extensive practical experience of a tool before testing (Morris *et al.*, 2008), provided examples of outcomes of ratings (Crossley *et al.*, 2011), as well as given power point presentations and a couple of hours direct training (Padua *et al.*, 2009). Providing raters with greater instruction around operational differences and providing potential examples of each observable segmental faults (e.g. trunk dominant, hip avoidant, knee dominant) may assist raters clinically in standardising their scoring methods. This is particularly evident around questions 7 and 8 and the SLS results where identifying minor deviations in movement is more difficult, and where SLL reliability and agreement is better presumably due to the larger deviations seen within that movement pattern and being more discernible. Future research and recommendations for the development of the QASLS tools should include standardised examples and education on criteria example to maintain more consistent and objective analysis to improve agreement rating.

3.5 Conclusion

The results of this present study provide evidence that 2D kinematic variables from both the frontal and sagittal plane can be measured with moderate to excellent within and between-session reliability and intra and inter-rater reliability during unilateral loading tasks of the lower limb, although this did not fully extend to the upper limb. Also, further questions are raised around the clinical utility of monitoring variables in isolation, the examination of multiple variables is warranted to evaluate whole complex movements with the incorporation of the kinetic chain.

The qualitative method of analysing movement quality has demonstrated similar levels of within and between-session reliability and intra-rater reliability. Trunk lean, hip adduction angles and knee valgus as observed by QASLS were also shown to have significant relationships to 2D measurements during the SLS task. Sagittal trunk angles, hip adduction and significant knee valgus correlated significantly for SLL. As correlations between QASLS scores and 2D parameters were stronger for SLS this task might be more transferable to clinical practise initially. This indicates that practitioner observations with the QASLS tool during single-leg load tasks is similar to that observed during 2D video analysis. This is encouraging as qualitative visual observation by practitioners appear to be reflective of quantitive measures. Since the majority of measurement of movement quality performance occurs in a practical, not laboratory-based environment, gaining an understanding of this relationship is important.

The QASLS tool is recommended as a more accessible, portable method of analysing movement quality by individual raters within a clinical setting. Classifying movement through segmental dichotomous approach appears to result in an agreement that is better than chance for within-rater measurements. Whilst PEA was acceptable for inter-rater agreement, results should be viewed with caution as continued research is needed to develop education pieces around the QASLS tool. Future efforts should be made to provide greater explanation and understanding of the operational definitions within the tool, once this has been established inter-rater agreement should be cleaner and elevated to more acceptable levels. A final limitation of the study was the potentially homogenous population selected, and whilst not unrepresentative of a healthy, elite sporting population, it is unclear how QASLS tool may be influenced by more heterogenous samples such as injured populations or adolescent younger age groups. Future additional investigation within these groups will provide greater understanding into the application and continuing development of visual observation of movement quality.

Chapter Four

4.0 The influence of growth and maturation on 2D and qualitative measures of unilateral task performance in multisport youth athletes

Following on from the process of validating the methodology in Chapter Three, the current study aims to further explore the impact of growth and maturation on the performance of two unliteral tasks by a youth population using a cross-sectional sample of multisport youth athletes. It is anticipated this study will address aims 1 and 2 of the thesis, by developing understanding of optimal application of the profiling tool, through consideration of the complex context specifically found within an adolescent population.

4.1 Introduction

Musculoskeletal injuries remain a significant problem within the adolescent and youth population, with injury incidence, time loss and incidents of cessation from the sport all together appearing to be on the increase year on year (Rejeb *et al.*, 2017). The sharp increase of the professionalisation and competitive nature of youth sport has led to a substantial increase in the number of youth athletes sustaining weekly injuries and a significant increase in concerns regarding injury risk and incidence within this group. Furthermore, in youth athletes, 20% of all injuries result in 2 months away from the sport (Von Rosen, Heijne, *et al.*, 2018). This changing shift towards competitive success within youth sport is placing increased physiological and psychological pressure on the individual athlete themselves (Difiori *et al.*, 2014), as focus on high- intensity training and competition edges down the continuum towards the younger age groups (Von Rosen, Heijne, *et al.*, 2018), the prevalence of inherent injury risk, overuse and burnout have increased with it (Rejeb *et al.*, 2017; Von Rosen, Heijne, *et al.*, 2018). Unlike the elite adult sporting population research into the epidemiology of the youth sporting and adolescent athlete is less. Lower Limb injuries account for 29-89% of all injuries sustained within this age group (Agresta *et al.*, 2017). Rejeb *et al.*, (2017) found that within 166 multisport athletes aged 12-18, 67% of sustained injuries occurred within the lower limb, with even higher rates of lower limb injury (83%) reported in sports specialisation athletes that year-round train in a single sport (Palmer-Green *et al.*, 2015; Lam *et al.*, 2017).

Deficits in neuromuscular control (NMC) during unilateral tasks such as landing have been linked to injury causation in adults (Zazulak *et al.*, 2007; Hewett *et al.*, 2016), with similar causation links being shown in adolescents (Anu M. Räisänen *et al.*, 2018a), NMC and dynamic control of the lower limb particularly whilst under load, is, therefore, a key consideration regarding risk factors for both acute and chronic lower limb injury.

The growth spurt associated with adolescents has been indicated as a risk factor for injury (Difiori *et al.*, 2014; Kozieł and Malina, 2018) due to the potentially rapid changes related to limb length, the centre of mass, body mass and stature changes and modified NMC strategies encountered with sensorimotor maturation (Quatman-Yates *et al.*, 2012). These maturational changes are thought to directly impact motor performance. Although this concept is debated, as it remains unclear if the growth spurt itself is enough for increases in injury risk or whether it is the result of other cumulative factors such as training load, competition environment, chronological age, state of behavioural change (Cumming *et al.*, 2017).

Whilst the process of growth is a non-modifiable factor, NMC is still the most modifiable factor for practitioners within this population -although likely to be the most varied (Anu M. Räisänen *et al.*, 2018a). Therefore, its continual assessment by practitioners via simple and effective means remains paramount. Due to the nature of maturation, a developing athletes NMC and movement quality may be significantly impacted during the growth process (Agresta *et al.*, 2017). To avoid the wrong inference concerning task performance and injury risk factors within this population, during any movement quality or assessment test, and individual's biological maturation status is an important consideration.

Assessment of NMC via biomechanical factors have been considered with maturational status by a handful of authors, but these have been limited to the reporting of one reductionist kinematic variable, usually at the knee during a SLS (Agresta *et al.*, 2017; Anu M. Räisänen *et al.*, 2018a; Ellenberger *et al.*, 2020) or within the bilateral conditions of a drop of tuck jump (Read *et al.*, 2016; Ellenberger *et al.*, 2020). As evidenced in chapter 3, this isolated reporting of 2D or force-plate derived parameters is limited in its approach to evaluate a movement pattern or provide further holistic insight into the status of the movement system as a whole. There remains a paucity of information regarding how NMC might change during the adolescent period, the influence of maturation of the whole movement pattern specifically unilateral tasks remains relatively unknown.

Only one paper has investigated qualitative evaluation of a unilateral pattern within an adolescent cohort with consideration of maturational influences. Agresta *et al.*, (2017) concluded that maturational status did not influence SLS performance in 10-14-year olds, but chronological age did with younger children demonstrating the poorer performance of a squat than older children. This suggests that great variation in performance between growth groups that might be discernible when assessed via a qualitative method, and that further assessment of whole movement patterns and movement assessment tools that can accommodate the evaluation of growth are warranted.

To date, no other research has specifically been published about the QASLS tool within a youth population. Understanding how maturational status might affect test performance on movement quality is crucial considering the potential NMC changes that occur within this population (Cumming *et al.*, 2017). The results of chapter three have demonstrated good reliability and validity against 2D parameters, although this is item dependant to segments involving the trunk, hip and knee, which still embody key risk factors for LL injury within a youth population (Myer *et al.*, 2008; Dingenen, Staes, *et al.*, 2018; DiCesare, Montalvo, Barber Foss, Thomas, Hewett, *et al.*, 2019). During maturation, and particularly the adolescent growth spurt, body mass, limb length and moments of inertia all can change fairly rapidly (Difiori *et al.*, 2014), furthermore the non-linear regression and progressions seen during these physiological changes may also impact time frames on developing full neuromuscular, intersegmental, interlimb co-ordinational control (Quatman-Yates *et al.*, 2012). Therefore, to meet the second objective of the thesis, the first aim of this study was to examine the effects of growth and maturation on consistency of performance on 2D kinematic variables and QASLS qualitative assessment scores, to identify population related differences in the measurement tools during the two unilateral tasks. This could have important implications on determining if the QASLS tool would be valuable in practice, or if the variability of movement encountered during growth and maturation would prove too much to effectively determine and interpret it.

Within the QASLS framework, operational definitions are provided in conjunction to the movement strategies observed at each segmental level, along with instruction relating to compound dichotomous scoring, however, Herrington, Myer and Horsley, (2013) did not allude to specific calculation methods of QASLS scoring to determine the computation of between repetition and multiple repetitions scoring. Anecdotally the QASLS system is advocated to be used so that the compound score, regardless of if from a singular or multiple effort, is comprised of the total number of strategies required by an individual to complete the task irregardless of frequency. Namely, if 3 or 5 repetitions of a unilateral task are completed, even if a sub-optimal strategy is observed once or five times the practitioner awards 1 mark, resulting in the cumulation of a "sub-optimal" trial. Although previous rater-reliability articles investigating the QASLS tool (Almangoush, Herrington and Jones, 2014; Herrington and Munro, 2014; Horobin and Thawley, 2015) during unilateral squatting and landing tasks presented the number of evaluated repetitions (3 or 5). It was unclear if the authors used the collective "highest" score method, or an average of the 3-5 repetitions to designate the compound QASLS score. The best method for compound QASLS scoring has yet to be fully elucidated, to establish further factors that impact the application of qualitative assessment in the youth adolescent population, and to meet the first and second aims and objectives of the thesis, further clarity regarding calculation methods must be sought.

Within sports science literature, an average or mean of 3 or more trials is usually calculated by practitioners when using a variety of kinetic and kinematic measures (Munro, Herrington and Carolan, 2012; Gwynne and Curran, 2014), this has also been shown to be similar in the Qualitative literature with the compound score being calculated as an average across trials during the landing error scoring system (LESS) (Padua *et al.*, 2009; Mauntel *et al.*, 2017) the tuck jump assessment (TJA) (Lininger *et al.*, 2017)and the functional movement screen (FMS) (Wiese *et al.*, 2014; Scattone Silva *et al.*, 2017).

Lockhart and Stergiou, (2013) described movement variability "as the normal variations that occur in motor performance across multiple repetitions of a task." Therefore, when determining an individual's performance understanding the relationships between calculation methods is important not only for feasible practical application but in terms of gaging performance impact. Whilst an overall compound or mean score may indicate innate levels of movement quality, it provides minimal information about bandwidths of movement performance. Repetition scores are commonly reported in the literature and can be useful when determining how much a participant deviates from their mean.

When determining an individual's performance understanding the relationships between calculation methods is important not only for a feasible practical application but in terms of impacting performance. Between-repetition scores are commonly reported in the literature and can be useful when determining how much a participant deviates from a mean. Whilst a cumulative "worst" score method might be more useful for reflection of performance (you are only as good as your worst repetition), understanding differences between an individual's performance concerning learning effects and range of performance is also important.

The average score or mean of 5 repetitions is commonly used in the scientific literature, but information regarding its use in the qualitative literature is limited predominantly to bilateral task evaluation (Padua et al., 2009). There is minimal information regarding the effects of the calculation methods of QASLS. Providing a final QASLS score of an adolescent's task performance based on their average score may result in concealment of their true variability as the performance bandwidth becomes neutralised by the mean. Therefore, the secondary aim of this study was to explore if QASLS scores significantly differed between calculation methods and if there was a relationship between both methods, to establish if the application of the QASLS tool as it is inferred in the adult population is also appropriate to be applied the same way in a youth population This could have important implications in determining the effective use of the QASLS tool within an adolescent population as without this normative performance any changes in performance cannot be evaluated properly. Additionally, furthering practitioner understanding around non-linear methods of movement analysis, a necessary approach to further identifying the interactions of isolated and whole movement components how these interactions may relate to adolescent injury risk (Bittencourt et al., 2016).

4.2 Methods

Summary of Study Aims

The aim of the study was to understand the associations between growth and maturation on the movement quality of two unilateral tasks in multisport athletes. The secondary aim of the study was to establish the most applicable calculation methods of QASLS scoring for this population. It is expected that this study will contribute to the understanding of the application of this profiling tool in an adolescent population.

4.2.1 Participants

40 participants (aged 8-16 years, 24 male and 16 female) (table 1) from a school athlete academy volunteered to take part in the study. The athlete academy comprises a structured pathway for female and male athletes that provides formalised S&C sessions run by UKSCA accredited coaches to children between the ages of 7-19 from all sporting backgrounds. There is no minimal level of sporting participation and children attend 1 structured group session per week. All participants were required to be injury-free during testing, with parental consent, participant assent and physical/ParQ questionnaires collected before the commencement of testing. Following the first test session, five participants dropped out from the study due to competitive sporting commitments (n=3), no-longer wishing to partake in the study (n=1) and 1 individual who forgot testing was occurring and went home. The University of Salford research and ethics committee approved the study in accordance with the declaration of Helsinki (1983).

4.2.2 Research Design

A repeated measures experimental design was selected to determine between session and within-session consistency and variation of a range of 2D kinematic parameters and QASLS scores. Participants attended two testing sessions within their school facility three weeks apart, all participants completed the same warm-up set by the academy's strength and conditioning coach. Heights and weights were collected and conducted by the same researcher (GP) during each session. Participant task instructions were standardised but tailored to age appropriateness (see section 4.2.3). Task order was randomised, and 5 repetitions were analysed for data analysis. All testing sessions occurred at the same time of day, participants were encouraged to continue with their normal daily routines regarding nutritional and fluid intake.

4.2.3 Procedures

Test space

Was configured in the same way as the methods described in chapter three (section 3.2.1).

Movement Assessment Tasks the Single Leg Squat (SLS) and Single Leg Land (SLL)

The same movement assessment tasks were undertaken as those undertaken in chapter 3 (section 3.2.4 figures 3.3 and 3.4), using the same anatomical landmarks as described in section 3.2.3. the movement task order was randomly determined by a coin toss. Those aged 12 or older were provided with the same verbal instructions as described in section (3.2.4), those aged 10 or under were provided with age-appropriate instruction (Appendix C) and a physical demonstration of three repetitions of the task by the clinician (GP). Those aged 11 were initially instructed via the task instruction used in chapter three, however, if they struggled to complete the tasks after 3-5 warm-up reps, the age-appropriate language was utilised and an additional warm-up set allowed. Research (Difiori *et al.*, 2014) has demonstrated that cognitive development is not linear, and evidence of it must occur to allow a young participant to follow directions. The cut off age of ten was chosen as this differentiates participants of primary and secondary school age, eleven-year-olds were provided with both task instructions as within the UK school system children aged 11 may be in primary or secondary environments. The careful selection of language was chosen to ensure that younger participants could understand and recall the instructions to execute testing, so they did not feel testing was beyond their ability and therefore be limited in the opportunity to participate.

Anthropometry and Biological Maturation

Anthropometric data (Table 4.1) was collected before each test session, body mass (kg) was collected on calibrated electronic scales (Seca 813, Hamburg, Germany), sitting and standing height (cm) to the nearest 0.1cm were collected via a portable stadiometer (Seca 213 portable height measure, Hamburg, Germany). Leg length was calculated as stature minus sitting height (Mirwald *et al.*, 2002).

Participants maturation stage was assessed using two non-invasive methods of maturity offset and the predicted percentage of adult height (%PAH) to try to estimate the timing of maturity at the time of testing (Khamis and Roche, 1994; Mirwald *et al.*, 2002). Maturity offset, or the time before or after PHV, was calculated for each participant with the sex-specific equations developed by Mirwald *et al.*, (2002). To define maturity status by offset means, a ±1.0 year band of the respective means was used to identify pubertal status, and approximate standard deviations for pre and post pubertal participants (Malina, Bouchard and Bar-Or, 2004; Myburgh, Cumming and Malina, 2019). To determine status of the growth spurt by %PAH the grouping methods of Parr *et al.*, (2020). Whilst each method comes with its limitations (± 0.5 years error measurements for PHV offset, overestimated parental-heights for %PAH), the maturity equations (Fig 4.1) has been used successfully in previous research within the paediatric sporting populations. To ensure as much stability as possible was present for use of %PAH, the same clinician (GP) collected all height and weight measurements of each participant, parental heights were also collected by the same clinician using the same stadiometer where possible. Participants were then allocated to Pre-PHV (offset < - 1 year) Circa-PHV (between -1-+1 years) or Post-PHV (>1+ years) (Malina, Bouchard and Bar-Or, 2004; Myburgh, Cumming and Malina, 2019) groups in relation to their years from PHV, and their growth spurt status (Pre: <85%, Circa 85-96%, Post: >96%) (Parr *et al.*, 2020) at the first testing session. Following allocation, and the withdrawal of some participants, the post-PHV group only comprised of 3 participants following the completion of testing at the second session. As this was not deemed enough to make any useful comparison, the post-PHV group were omitted from further analysis.

Defining Multisport status

The classification of the multisport or single-sport athlete remains poorly defined, with numerous definitions documented within the literature and minimal clarity around inclusion criteria for definitions (Brenner *et al.*, 2007, 2016; Buckley *et al.*, 2017). Athletes have been classified solely on the number of sports they partake in, with Hall *et al.*, (2015) classifying

Table 4.1: Anthropometric and Maturity Characteristics (mean ±SD)

	Pre-PHV (n=15)	Circa-PHV (n=17)	Post PHV (n = 3)
Chronological age (years)	10.6 ± 1.7	13.1 ± 1.3	14.7 ± 0.8
PHV offset (years)	-2.6 ± 1.3	-0.3 ± 0.5	2.2 ± 0.4
Predicted Adult Height (%PAH)	0.81 ± 0.09	0.9 ± 0.0	0.99 ± 0.0
Mass (Kg)	40.2 ± 9.0	49.3 ± 10.9	59.6 ±11.4
Height (cm)	146 ± 10.7	161.1 ± 10.7	165.9 ± 1.3
Leg Length (cm)	75.7 ± 7.0	82.8 ± 5.9	82.5 ± 3.5
Biological Sex	Male = 9, Female = 6	Male = 9, Female = 8	Male = 2, Female = 1

Note: cm = centimetres, Kg = kilograms, SD = Standard Deviation, %PAH = percentage of predicted adult height

Maturity Offset Male: =
-9.236 + [0.0002708 x leg length and sitting height interaction]
- [0.001663 x age and leg length interaction]
+ [0.007126 x age + sitting height interaction]
+ [0.02292 x weight by height ratio]

Maturity Offset Female: =
-9.376 +[0.0001882 x leg length and sitting height interaction]
+ [0.0022 x age and leg length interaction]
+ [0.005841 x age and sitting height interaction]
-[-0/002658 x age and weight]
+ [0.07693 x weight by height ration]

Figure 4.1: Example of none invasive maturity equations used. *Taken from Mirwald et al., (2002)*

participants as multisport athletes if they competed in more than 1 sport. Whereas DiCesare *et al.*,(2019) classified athletes by both numbers of sports and number of years of participation with participants classified as multisport athletes if they competed in at least 2 sports for at least two years in each. As some of the participants within this study where younger than those in the above papers, this studies definition was slightly different as 2 years of sporting participation in some of the youngest participants were deemed unrealistic and incomparable to some of the older participants. At the first test session participants and their parents were asked to document “What organised sport they played regularly” and “how old where they when they started playing?” Participants were classified as multisport if they identified 1 sport as their “main” sport and participated in at least 1 or 2 additional sports(s), that involved the attendance at 1 organised training and or game session a week, across multiple months of the year.

2.4 Statistical Analysis

All statistical analysis was processed via SPSS for Mac (version 25, SPSS Inc, Chicago, IL), with additional CV% ICCs, 95% CI, SEM and SDD values calculated via a custom-made spreadsheet (Microsoft Excel Version 16.16.22). The dependant variables evaluated where the frontal (LTL, HADD, FPPA) and sagittal (TFA) 2D kinematic parameters and compound and component QASLS scores evaluated in chapter 3. Whilst all 2D variables were evaluated in the youth population, for ease of data presentation for the reader only the 2D variables validated in chapter 3 are presented in chapter 4. A full table of all 2D kinematic variables is available for comparison and can be found in Appendix D.

It is important to note that whilst reliability statistics are presented, they have been used to evaluate consistency in 2D Kinematic and QASLS scoring performance rather than methodological reliability analysis. The concept of using reliability statistics to demonstrate performance consistency (Mehta *et al.*, 2018) has been successfully demonstrated in force plate measures in youth soccer (Read *et al.*, 2016) and within the aviation industry when monitoring the consistency of novice pilot flight performance (Smith, Niemczyk and McCurry, 2018). ICC values were interpreted according to the criteria set by (Koo and Li, 2016). The analysis was undertaken on both whole group data set and growth group scores by the unilateral task. Methodological reliability analysis in chapter three has previously demonstrated differences between limbs. Also, knowledge around individual limb performance is of interest to practitioners, as unilateral limb positions remain the most common positions for the majority of lower limb overuse and traumatic injury occurrence (Whatman, Hume and Hing, 2013), therefore analysis and data for each limb is presented separately. The mean and standard deviation of all 2D and QASLS qualitative measures are presented unless otherwise stated. Normality for each variable was assessed by Shapiro-Wilk test (P >.05).

2D Data

To determine significant differences in performance consistency between trials, paired-samples t-tests were selected for the normally distributed parameters, and Wilcoxon test for those that were non-normally distributed, a p-value of < 0.05 was selected for all tests. All 2D SLS parameters were normally distributed except for the upper limb variables. However, for SLL only Hip Adduction angle (HADD), FPPA, KFA and ADF met normal distribution assumptions. Between-session consistency was additionally determined via CV% and ICC to determine rank order, with 95% CI, SEM and SDD also reported. CV <10% has been cited as an acceptable boundary within sports science (Turner *et al.*, 2015). Between PHV group differences were assessed via independent samples t-tests for the normally distributed SLS 2D parameters, and Mann Whitney U tests for the non-normally distributed SLL 2D parameters. Mean and standard deviations for all 2D parameters are presented for the whole group and PHV group data.

QASLS Data

Like the 2D data, the analysis was undertaken on the whole group and PHV group data. QASLS scores were normally distributed for whole and PHV groups and both limbs and task. Between trial consistency of QASLS scores was completed on 2 different calculation methods of scoring, the mean of the 5 repetitions method and the highest score method. Separate paired samples t-tests were completed on each calculation method to determine if there were significant performance differences between test occasions. Between PHV group differences were assessed via independent samples t-tests for the normally distributed mean of the 5 repetitions method for SLS and SLL, and the R SLL via the highest score method. As QASLS Scores for L SLL in the whole group data, and R SLL for both PHV groups during the highest score method were found to violate tests of normality (p= < .05) Mann Whitney U tests were completed on the worst score method for SLL. Within-subject variation was reported as CV% of the 5 repetitions instead of the individual repetitions QASLS scores and was expressed as

CV% QASLS score. This allowed for comparison to the highest score method and is usually less affected by operator error (Hopkins, 2000).

To establish within-session variability of within-group QASLS Scores, a one-way repeated measure analysis of variance (ANOVA), with Bonferroni correction applied, was completed on test session 1 scores to identify any existence of differences between the scores for each of the 5 repetitions. A Friedman test was completed on left single-leg land within the whole group and Circa-PHV group due to non-normal distribution, to establish differences between repetitions.

Three-way analysis of variance (ANOVA) was conducted to identify within-session variability of QASLS Score between the 5 repetitions between PHV groups according to three factors, Growth Group (with 2-factor levels Pre-PHV and Circa-PHV), Task (with 2-factor levels SLS and SLL) and Limb (with 2-factor levels right and left). CV% QASLS scores were normally distributed (P= >.05) for growth, task and limb groups as assessed by Shapiro-Wilk test. There was homogeneity of variances for CV% QASLS scores for all group combinations of growth, limb and unilateral tasks as assessed by Laverne's test for equality of variance, p = .379. Following the testing of all interactions and removal of non-significant results, an additional simple interaction was used to recalculate the ANOVA, pairwise comparisons were made with Bonferroni adjustment applied. Statistical Significance was set at p = <.05 for both tests.

Calculation Method of QASLS Score

To explore the comparison of calculation methods, Bland Altman plots were created to establish limits of agreement between the two calculation methods and evaluate the mean bias via visual representation, by plotting the difference between the mean of the 5 repetitions and highest score against the mean of the 5 repetitions and highest score. Pearsons correlation coefficients (R) for the normally distributed SLS and R SLL and Spearman's correlation (R2) for the L SLL were completed to determine the relationship between the mean of 5 repetitions and highest score method in QASLS scores. Correlations were interpreted as negligible (<0.10), weak (0.10-0.39), moderate (0.40-0.69). strong (0.70-0.89) and very strong (>.90) (Overholser and Sowinski, 2008; Schober, Boer and Schwarte, 2018).

4.3 Results

4.3.1 2D Data

An overview of the descriptive statistics for the 2D kinematic parameters in pre and circa-PHV multisport athletes is presented in table 2 for SLS and table 3 for SLL. No significant differences were found in 2D parameters between the 2 test occasions by unilateral task or growth group. Between session consistency was moderate to good (ICC=0.58-0.81) for frontal and sagittal plane trunk angles, and moderate (ICC= 0.58-0.68) for left limb frontal plane hip and knee kinematics during the squatting task in the pre-PHV group. This consistency was not observed for frontal plane hip and knee variables with ICCs crossing zero. In the circa-PHV group between-session consistency was good to excellent (ICC= 0.88-0.95) for the sagittal plane and moderate (ICC= 0.56-0.69) for frontal plane 2D trunk variables during squatting. Other frontal plane hip and knee variables were poor (ICC = 0.21-0.59) for both limbs.

During unilateral landing, sagittal plane trunk lean performance consistency was good (ICC= 0.71-0.85) for the pre-PHV group and moderate to good (ICC=0.54-0.76) for the circa-PHV group. Pre-PHV athletes also displayed moderate to good (ICC=0.52-0.75) frontal plane trunk consistency but this was not observed in the circa-PHV athletes where performance consistency to the right was moderate (ICC=0.60) but poor to the left (ICC=0.35). Frontal plane 2D variables for the hip and knee were poor (ICC = 0.08-0.42) in performance consistency, during landing in the pre-PHV group, but graded as moderate (ICC= 0.65-0.70) in the circa-PHV group, indicating a slightly improved frontal plane performance consistency.

SEM values were ≤10° for all parameters across both PHV groups and tasks, and whilst measurement error appeared promisingly low, ICCs, 95%CI and CV% demonstrate large variations in performance. CV% ranges were high, with at least 3 of the 4 2D variables in each PHV group surpassing the ≤10% values proposed within the literature (Turner et al., 2015) for both the squatting (Pre-PHV=6-30.6%; circa-PHV= 8.9-32.3%) and landing (Pre-PHV=7.6-40.3%; circa-PHV=4.9-33.3%) tasks. The within-individual variation of unilateral task performance would be very high, and overall unilateral task performance would be consistently inconsistent.

Table 4.2 Descriptive statistics for between session consistency SLS 2D parameters for whole, pre and circa-PHV group data

			WHOLE GROUP				
FRONTAL PARAMETERS	**TEST 1 (°)**	**TEST 2 (°)**	**ICC**	**CV%**	**95% (CI)**	**SEM (°)**	**SDD**
Lateral Trunk Lean Right	32.5 ± 10.6	33.7 ± 10.0	0.59	13.6	0.08-0.85	6.6	18.3
Left	28.3 ± 8.0	29.2 ± 7.6	0.75	9.3	0.36-0.92	3.9	10.8
Hip Adduction Right	59.2 ± 8.1	59.8 ± 9.7	0.06	11.1	-0.49-0.57	8.7	24.1
Left	70.4 ± 10.3	66.4 ± 11.3	0.38	9.6	-0.19-0.76	8.5	23.7
FPPA Right	25.0 ± 8.4	21.3 ± 8.8	0.16	29	-0.41-0.64	7.9	21.9
Left	16.3 ± 8.1	18.3 ± 10.2	0.52	30.7	-0.02-0.82	6.3	17.6
SAGITTAL PARAMETERS							
Trunk Flexion Angle Right	43.8 ± 19.3	45.7 ± 18.8	0.82	16.9	0.51-0.94	8.1	22.4
Left	42.1 ± 20.4	42.2 ± 18.3	0.90	12.7	0.71-0.97	6.2	17.1
			Pre-PHV GROUP				
FRONTAL PARAMETERS	**TEST 1 (°)**	**TEST 2 (°)**	**ICC**	**CV%**	**95% (CI)**	**SEM (°)**	**SDD**
Lateral Trunk Lean Right	30.9 ± 7.7	31.6 ± 9.6	0.73	9.8	0.32-0.91	4.6	12.6
Left	26.0 ± 6.9	27.6 ± 6.8	0.81	8.5	0.49-0.94	3.0	8.2
Hip Adduction Right	58.1 ± 8.0	60.5 ± 9.2	-0.25	12.6	-0.69-0.33	9.6	26.7
Left	71.4 ± 9.6	69.5 ± 10.7	0.68	6.0	0.23-0.89	5.8	16.0
FPPA Right	27.0 ± 7.2	20.2 ± 6.5	-0.29	30.6	-0.71-0.29	7.8	21.7
Left	16.8 ± 7.3	17.0 ± 6.5	0.58	18.8	0.07-0.85	4.5	12.4
SAGITTAL PARAMETERS							
Trunk Flexion Angle Right	40.6 ± 16.6	41.3 ± 15.0	0.69	18.2	0.25-0.89	8.8	24.5
Left	35.9 ± 17.1	38.4 ± 14.1	0.77	18.8	0.44-0.91	7.5	20.7
			Circa-PHV GROUP				
FRONTAL PARAMETERS	**TEST 1 (°)**	**TEST 2 (°)**	**ICC**	**CV%**	**95% (CI)**	**SEM (°)**	**SDD**
Lateral Trunk Lean Right	35.2 ± 13.3	36.9 ± 10.4	0.56	16.8	0.04-0.84	8.0	22.0
Left	31.1 ± 9.0	31.4 ± 8.0	0.69	10.3	0.25-0.89	4.7	13.1
Hip Adduction Right	61.3 ± 8.1	59.9 ± 9.8	0.28	8.9	-0.30-0.71	7.6	21.2
Left	69.5 ± 11.5	62.6 ± 11.0	0.21	12.6	-0.36-0.67	10	27.7
FPPA Right	23.2 ± 9.4	20.3 ± 8.4	0.59	24.9	0.08-0.85	5.7	15.7
Left	16.7 ± 8.9	20.7 ± 11.6	0.48	32.3	-0.07-0.81	7.5	20.7
SAGITTAL PARAMETERS							
Trunk Flexion Angle Right	48.6 ± 21.9	51.1 ± 21.3	0.88	14.9	0.65-0.96	7.6	21.1
Left	48.9 ± 22.0	47.4 ± 21.0	0.95	9.6	0.84-0.98	5.0	13.8

Table 4.3 Descriptive statistics for between session consistency for SLL 2D parameters for whole, pre and circa-PHV groups

			WHOLE GROUP				
FRONTAL PARAMETERS	**TEST 1 (°)**	**TEST 2 (°)**	**ICC**	**CV%**	**95% (CI)**	**SEM (°)**	**SDD**
Lateral Trunk Lean Right	27.2 ± 6.0	27.3 ± 5.3	0.52	8.0	-0.02-0.82	3.9	10.9
Left	25.7 ± 5.9	24.9 ± 6.3	0.33	13.8	-0.25-0.73	5.0	13.9
Hip Adduction Right	72.8 ± 8.1	72.7 ± 8.9	0.30	6.9	-0.28-0.72	7.1	19.7
Left	80.4 ± 7.9	77.9 ± 9.0	0.41	6.5	-0.16-0.77	6.5	18.0
FPPA Right	18.2 ± 8.1	17.7 ± 6.8	0.34	28.5	-0.14-0.78	6.3	17.4
Left	13.0 ± 6.8	12.7 ± 6.8	0.34	35.3	-0.23-0.74	5.5	15.3
SAGITTAL PARAMETERS							
Trunk Flexion Angle Right	28.3 ± 12.0	31.6 ± 12.5	0.69	21.0	0.25-0.89	6.8	18.8
Left	27.1 ± 13.1	28.7 ± 12.7	0.82	16.8	0.51-0.94	5.4	15.1
			Pre-PHV GROUP				
FRONTAL PARAMETERS	**TEST 1 (°)**	**TEST 2 (°)**	**ICC**	**CV%**	**95% (CI)**	**SEM (°)**	**SDD**
Lateral Trunk Lean Right	27.5 ± 7.9	25.8 ± 2.9	0.75	8.9	0.36-0.92	3.0	8.2
Left	25.4 ±7.6	23.2 ± 3.1	0.52	14.9	0.20-0.82	4.0	11.2
Hip Adduction Right	74.0 ± 7.1	72.0 ± 8.0	0.10	7.6	0.46-0.60	7.2	20.1
Left	81.3 ± 6.0	75.3 ± 9.5	0.42	8.2	0.14-0.78	6.0	16.7
FPPA Right	18.7 ± 8.7	18.2 ± 15.5	0.09	40.3	-0.38-0.66	8.0	22.3
Left	12.7 ± 8.2	13.5 ± 6.3	0.08	39.7	-0.39-0.65	7.0	19.5
SAGITTAL PARAMETERS							
Trunk Flexion Angle Right	25.2 ± 12.4	27.0 ± 11.1	0.71	20.6	0.29-0.90	6.4	17.7
Left	22.9 ± 12.6	23.8 ± 12.4	0.85	16.7	0.58-0.95	4.8	13.2
			Circa-PHV GROUP				
FRONTAL PARAMETERS	**TEST 1 (°)**	**TEST 2 (°)**	**ICC**	**CV%**	**95% (CI)**	**SEM (°)**	**SDD**
Lateral Trunk Lean Right	26.5 ± 4.9	26.8 ± 3.8	0.60	6.6	0.10-0.86	2.8	7.6
Left	24.9 ± 4.7	24.2 ± 4.1	0.35	11.3	-0.22-0.74	3.5	9.8
Hip Adduction Right	71.1 ± 8.6	74.2 ± 8.4	0.70	5.6	0.27-0.90	4.6	12.9
Left	78.6 ± 8.9	80.3 ± 8.9	0.70	4.9	0.25-0.90	4.9	13.5
FPPA Right	18.8 ± 9.1	19.0 ± 8.2	0.65	23.1	0.18-0.88	5.1	14.2
Left	14.1 ± 7.8	14.0 ± 7.5	0.46	33.3	-0.10-0.80	5.6	15.6
SAGITTAL PARAMETERS							
Trunk Flexion Angle Right	30.4 ± 11.1	33.9 ± 11.0	0.54	22.6	0.01-0.83	7.8	21.5
Left	30.1 ± 13.5	32.2 ± 10.7	0.76	16.9	0.38-0.92	5.9	16.5

Pre-PHV athletes generally displayed less frontal and sagittal trunk angles but larger FPPA angles during squatting for both limbs compared to the circa-PHV groups (tables 4.2 & 4.4). This was also evident for frontal FPPA and sagittal TRA during the landing task (tables 4.3 & 4.5). Despite the different values being displayed between PHV groups, at p=<.05, an independent samples t-test revealed no significant differences in any 2D kinematic parameters between PHV groups during either unilateral task (tables 4.4 & 4.5).

4.3.2 QASLS Data

Due to the novelty of the QASLS tool, consistency of unilateral task performance as assessed by QASLS compound scoring was analysed via two calculation methods of "the mean of 5 repetitions" and "highest score" method.

The results of the paired samples t-test assessing QASLS scores via the mean of 5 repetitions method are shown in table 4.6. Performance consistency during squatting was poor (ICC=0.12-0.34) for pre-PHV athletes and poor to moderate (ICC=0.28-0.61) for circa-PHV athletes respectively. During the landing task performance consistency worsened in the pre-PHV group with ICCs crossing zero (ICC= -0.21—0.46), but improved to moderate for the circa-PHV group (ICC=0.60). No statistically significant differences were deduced between sessions for either the SLS (pre-PHV group right limb p=.817, left limb p=.483; circa-PHV group right limb p=.715, left limb p=.624) or SLL (pre-PHV group right limb p=.521, left limb p=.754; circa-PHV group right limb p=.073, left limb p=.958). Circa-PHV athletes displayed lower cv% (CV% 13-22.9) than the pre-PHV group (CV% 17.9-29.6), however, both groups surpassed the recommended ≤10%CV values (Turner et al., 2015) for all tasks and limbs revealing high-performance variability in all groups. Independent samples t-tests revealed no statistically significant difference in unilateral task performance between PHV groups when analysed by the mean of 5 repetitions method (RSLS, p=.647; LSLS, p=.592; RSLL, p=.099; LSLL, p =.138).

With the highest score method, there were no statistically significant differences in between-session performance consistency as assessed by paired sample t-test for either task or limbs

(Table 4.7) Between-session performance consistency was poor (ICC=-0.29-0.20) for both unilateral tasks in the pre-PHV group and moderate in the circa-PHV group (ICC=0.50-0.57).

CV% exceeded accepted values (≤10%) in both groups and limbs. Circa-PHV group athletes presented lower CV% values (14.3-23.9%) than pre-PHV athletes (21.3-30.3%). CV% values were lower during the SLL tasks in both PHV groups (table 4.7), suggesting task-related performance differences between PHV groups. There were significant differences in compound QASLS scoring via highest score method during both unilateral tasks and limbs as assessed by independent samples t-test (Table 4.8).

An overview of the within-session consistency across the 5 repetitions of trial 1 is presented in table 4.9. At P<.05, a one-way ANOVA with Bonferroni correction and Freidman's test revealed no significant differences in between repetition compound QASLS scores in either pre or circa-PHV athletes during either unilateral task or limb. Indicating within-session performance consistency.

A three-way ANOVA between growth group, unilateral task and limb demonstrated no statistical significance in within-session performance consistency across the five repetitions (F (1,112=.104, p=.748) however there was a statistically significant interaction between growth groups and unilateral task (F(1,112) =1.152,p=.013)(figure 4.2). Data is mean and standard error unless otherwise stated. The simple main effect of PHV group CV% QASLS score was statistically significant during the unilateral landing task (F (1,112) =3.849, p=<.005), but was not during the unilateral squatting task (F(1,112) =.178,p=.674). Pairwise comparisons were made with Bonferroni correction. During landing, there was a significant (p=.042) difference of 8.7% (95%CI,0.09-17.6%) in mean CV% QASLS score between the circa-PHV (15.9 ±2.9%) and pre-PHV (24 ±3.3%) groups. During the SLS task, the 3.9% (95%CI, 14.4-22.3%) observed between the circa-PHV group (26.1± 8.8%) and pre-PHV group (22.1 ±2.7%) was not statistically significant (p=.674). There was no apparent within PHV group differences in performance consistency across the 5 repetitions (Table 4.9), but between PHV group differences existed during landing.

Table 4.4: Mean (SD), p-values for 2D parameters in SLS Pre and Circa-PHV groups

FRONTAL PARAMETERS	**Pre PHV**	**Circa PHV**	**t**	**df**	**Sig (2 -tailed)**
Shoulder Abduction Right Limb	23.8 ± 18.8	24.1 ± 16.1	.341	28	.736
Left Limb	27.1 ± 22.6	21.9 ± 9.4	1.1705	28	.099
Lateral Trunk Lean Right Limb	30.9 ± 7.7	35.2 ± 13.3	.708	25	.485
Left Limb	26.0 ± 6.9	31.1 ± 9.0	-.827	28	.415
Hip Adduction Right Limb	58.1 ± 8.0	61.3 ± 8.1	-1.113	28	.275
Left Limb	71.4 ± 9.6	69.5 ± 11.5	.491	28	.627
FPPA Right Limb	27.0 ± 7.2	23.2 ± 9.4	.988	28	.332
Left Limb	16.8 ± 7.3	16.7 ± 8.9	.052	28	.959
SAGITTAL PARAMETERS					
Shoulder Extension Right Limb	23.7 ± 18.7	47.3 ± 40	-1.344	25.1	.191
Left Limb	28.9 ± 27.2	41.4 ± 36	-.629	28	.534
Trunk Flexion Angle Right Limb	40.6 ± 16.6	48.6 ± 21.9	-.645	28	.524
Left Limb	35.9 ± 17.1	48.9 ± 22.0	-1.337	28	.192
Hip Flexion Angle Right Limb	107.3 ± 25.1	89.8 ± 31.9	.967	28	.342
Left Limb	111.5 ± 25.2	91.4 ± 35.0	1.288	28	.208
Knee Flexion Angle Right Limb	104.6 ± 10.1	98.1 ± 12.6	.978	28	.336
Left Limb	104.2 ± 12.5	101.5 ± 15.2	.337	28	.739
Ankle Dorsiflexion Right Limb	57.4 ± 6.1	59.1 ± 3.0	-.796	16.9	.437
Left Limb	57.0 ± 7.5	60.7 ± 4.0	-1.255	18.1	.226

Significance set at p=.05

Table 4.5 Mean (SD), p-values for 2D parameters in SLL Pre and Circa-PHV groups

FRONTAL PARAMETERS	**Pre PHV**	**Circa PHV**	**t**	**df**	**Sig (2 -tailed)**
Shoulder Abduction Right Limb	23.8 ± 18.8	20.8 ± 20.2	.186	28	.341
Left Limb	27.1 ± 22.6	22.3 ± 14.9	.312	28	.742
Lateral Trunk Lean Right Limb	30.9 ± 7.7	26.5 ± 4.9	.549	28	.837
Left Limb	26.0 ± 6.9	24.9 ± 4.7	.455	28	.652
Hip Adduction Right Limb	58.1 ± 8.0	71.1 ± 8.6	1.114	28	.408
Left Limb	71.4 ± 9.6	78.6 ± 8.9	1.077	28	.291
FPPA Right Limb	27.0 ± 7.2	18.8 ± 9.1	-.0540	28	.869
Left Limb	16.8 ± 7.3	14.1 ± 7.8	-.901	28	.483
SAGITTAL PARAMETERS					
Shoulder Extension Right Limb	23.7 ± 18.7	19.8 ± 20.1	-.665	28	.742
Left Limb	28.9 ± 27.2	22.7 ± 22.0	-1.372	28	.408
Trunk Flexion Angle Right Limb	40.6 ± 16.6	30.4 ± 11.1	-1.156	28	.157
Left Limb	35.9 ± 17.1	30.1 ± 13.5	-1.455	28	.113
Hip Flexion Angle Right Limb	107.3 ± 25.1	121.2 ± 17.6	1.204	28	.239
Left Limb	111.5 ± 25.2	121.6 ± 23.4	.839	28	.320
Knee Flexion Angle Right Limb	104.6 ± 10.1	116.9 ± 10	.252	28	.803
Left Limb	104.2 ± 12.5	119.8 ± 15.8	.282	28	.780
Ankle Dorsiflexion Right Limb	57.4 ± 6.1	67.2 ± 5.6	.359	28	.722
Left Limb	57.0 ± 7.5	69.4 ± 7.0	.134	28	.902

Significance set at p=.05

Table 4.6 Between session consistency of QASLS scores by mean of 5 repetitions method by Group

Task/Limb	Test1(SD)	Test2(SD)	ICC	95% CI	SEM	SDD	CV%
Whole Group (n=32)							
SLS R	4.7± 1.5	4.5 ± 1.2	0.25	(-0.10-0.55)	1.18	3.27	19.7
L	4.4 ± 1.7	4.5 ± 1.3	0.47	(0.15-0.70)	1.10	3.04	23.2
SLL R	4.0 ± 1.0	4.1 ± 1.1	0.33	(-0.02-0.61)	0.90	2.48	18.7
L	3.8 ± 1.1	3.7 ± 1.0	0.15	(-0.20-0.47)	0.96	2.67	19.4
Pre-PHV Group (n=15)							
SLS R	4.9 ± 1.6	4.8 ± 1.1	0.12	(-0.23-0.45)	1.32	3.66	17.9
L	4.3 ± 1.9	4.6 ± 1.3	0.34	(0.00-0.61)	1.33	3.68	26.9
SLL R	4.2 ± 0.8	3.9 ± 1.1	-0.21	(-0.52-0.14)	1.00	2.81	21.1
L	3.8 ± 1.2	3.6 ± 1.1	-0.46	(-0.69-0.14)	1.35	3.73	29.6
Circa-PHV Group (n=17)							
SLS R	4.6 ± 1.6	4.4 ± 1.2	0.28	(-0.07-0.57)	1.18	3.26	22.8
L	4.7 ± 1.5	4.5 ± 1.4	0.61	(0.34-0.79)	0.89	2.47	18.4
SLL R	3.8 ± 1.3	4.4 ± 1.1	0.60	(0.18-0.83)	0.77	2.15	17.8
L	3.9 ± 1.1	3.9 ± 1.0	0.60	(0.18-0.83)	0.65	1.79	13.0

Table 4.7: Between session consistency of QASLS scores by highest score method by Group

Task/Limb	Test 1(SD)	Test2 (SD)	ICC	95%CI	SEM	SDD	CV%
Whole Group (n=32)							
SLS R	5.8 ± 1.9	5.7 ± 1.5	0.15	(-0.20-0.47)	1.57	4.36	22
L	6.1 ± 2.1	5.8 ± 1.6	0.17	(-0.18-0.49)	1.69	4.68	24.4
SLL R	5.3 ± 1.4	5.4 ± 1.6	0.25	(-0.10-0.55)	1.30	3.61	19.3
L	5.2 ± 1.5	4.8 ± 1.2	0.26	(-0.34-0.34)	1.19	3.31	18.5
Pre-PHV Group (n=15)							
SLS R	6.1 ± 2.1	5.9 ± 1.6	0.20	(-0.33-0.63)	1.70	4.71	21.3
L	6.0 ± 2.4	6.0 ± 1.6	-0.16	(-0.61-0.37)	2.20	6.09	30.3
SLL R	5.6 ± 1.2	4.9 ± 1.5	-0.06	(-0.54-0.45)	1.43	4.96	23.7
L	4.9 ± 1.3	4.6 ± 1.3	-0.29	(-0.69-0.24)	1.48	4.11	24.9
Circa-PHV Group (n=17)							
SLS R	5.6 ± 1.8	5.5 ± 1.3	0.50	(0.04-0.75)	1.56	4.34	23.9
L	6.4 ± 1.9	5.7 ± 1.6	0.54	(0.10-0.80)	1.19	3.30	19.4
SLL R	5.0 ± 1.5	5.8 ± 1.6	0.55	(0.11-0.81)	1.04	2.88	16.7
L	5.4 ± 1.7	5.1 ± 1.2	0.57	(0.14-0.82)	0.96	2.67	14.3

Table 4.8 Differences and P-values between PHV Groups in QASLS worst score calculation method

Task/Limb	**Pre-PHV**	**Circa-PHV**	**Sig. (2-tailed)**
SLS			
R	6.1 ± 2.1	5.6 ± 1.8	.018
L	6.0 ± 2.4	6.4 ± 1.9	.019
SLL			
R	5.6 ± 1.2	5.0 ± 1.5	.014
L	4.9 ± 1.3	5.4 ± 1.7	.042

Scores expressed as mean and (SD). Significance set at p=<.05

Table 4.9 Trial 1 mean and SD values for the 5 repetitions for both limbs and unilateral task by Whole group and PHV group

Task/Limb	**Rep 1**	**Rep 2**	**Rep 3**	**Rep 4**	**Rep 5**
Whole Group (n=32)					
SLS R	4.3 ± 1.6	4.5 ± 1.9	4.7 ± 1.9	4.9 ± 1.8	4.8 ± 1.9
SLS L	4.3 ± 1.7	3.8 ± 2.2	4.5 ± 2.2	4.5 ± 2.2	4.5 ± 2.1
SLL R	4.0 ± 1.3	3.8 ± 1.7	4.0 ± 1.5	3.8 ± 1.7	4.1 ± 1.3
SLL L	3.5 ± 1.6	3.6 ± 1.7	3.8 ± 1.6	3.7 ± 1.2	3.8 ± 1.6
Pre PHV Group (n =15)					
SLS R	4.6 ± 1.8	4.6 ± 1.8	5.0 ± 2.3	5.4 ± 2.0	4.9 ± 1.9
SLS L	4.2 ± 2.1	2.8 ± 2.4	3.6 ± 2.7	3.3 ± 1.4	4.1 ± 2.4
SLL R	4.3 ± 1.6	3.7 ± 1.6	4.4 ± 1.2	4.2 ± 1.7	4.8 ± 1.3
SLL L	3.3 ± 1.4	3.8 ± 1.8	4.0 ± 1.6	3.5 ± 1.4	4.0 ± 1.7
Circa PHV Group(n =17)					
SLS R	4.2 ± 1.5	4.6 ± 2.0	4.5 ± 1.9	4.7 ± 1.8	4.8 ± 1.9
SLS L	4.4 ± 1.3	4.6 ± 1.9	5.0 ± 1.7	5.3 ± 1.9	4.5 ± 1.7
SLL R	3.7 ± 1.4	3.8 ± 1.9	3.7 ± 1.5	3.7 ± 1.7	4.3 ± 1.6
SLL L	3.8 ± 1.9	3.6 ± 1.7	3.8 ± 1.7	4.0 ± 1.0	3.8 ± 1.7

Significance set at p=.05

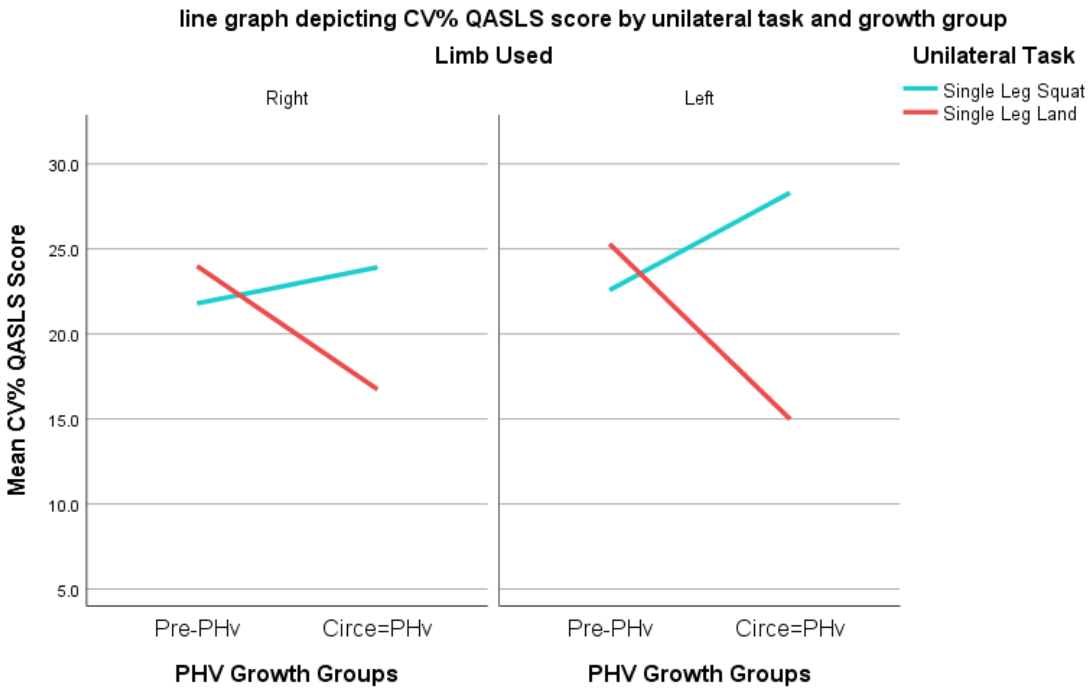


Figure 4.2: Line graph depicting CV% QASLS score by unilateral task and growth group

Calculation Methods

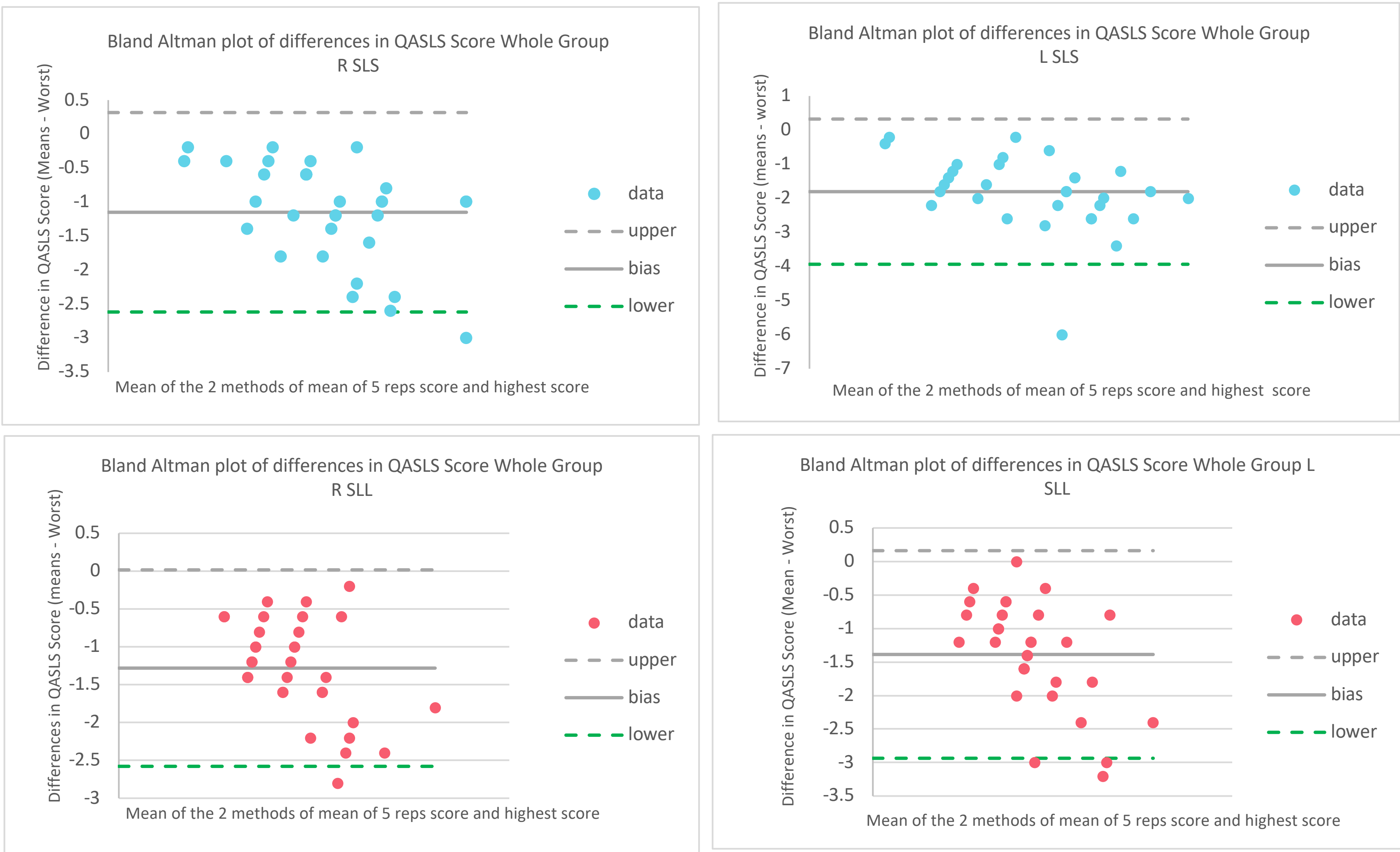
Correlations were run to assess the relationship between the two calculation methods and measured by either Pearson's correlation coefficient or Spearman's rank-order correlation (table 4.10). Whole group and subgroup PHV data are presented in table 4.14. Also reported are the limits of agreement in figures 4.3-4.14. There were statistically significant strong positive correlations between the 2 calculation methods of the mean of the 5 repetitions and worst score methods across all groups for both limbs and tasks (table 4.14, figures 4.15-4.17). Bland-Altman plots for pre (figures 4.3-4.6) and circa-PHV groups (figures 4.7-4.14) demonstrated that most data points were within 2 standard deviations for the differences and means of the calculation methods.

Overall QASLS scores collected via the worst scores method generally exceed those taken from the mean of the 5 repetitions method by an average of 1.5 points for Pre-PHV group and 1.3 points for Circa-PHV group as indicated by the grey solid lines on the Bland-Altman plots. Despite statistically significant linear relationships, the interval is wide in each test occasions indicating large variations in performance of tasks. Observed differences fall outside measurement error, indicating a strong relationship and levels of agreement between both calculation methods. This provides evidence for the justification of the current highest score method instructions contained within the QASLS that is more indicative of an individual's bandwidth of performance. Whilst presenting data as an average of mean scores is frequently common within the sports science literature. It appears that within the context of qualitative assessment, the presentation of a mean score could negate the bandwidth of individual performance, resulting in inaccurate interpretation and potential impact on clinical inference.

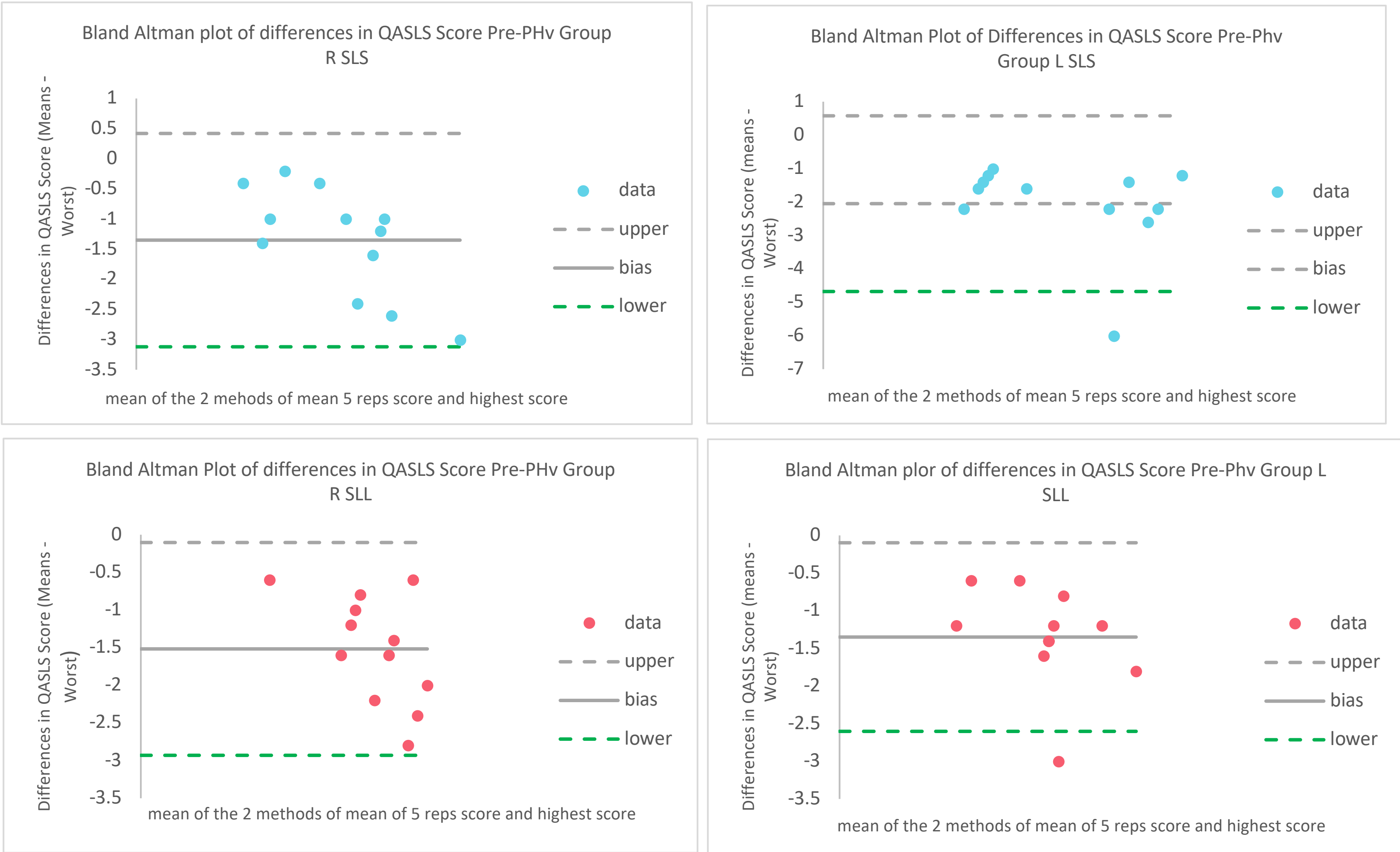
Table 4.10 Correlations and P-values relationships between QASLS calculation methods by PHV group

Task and Limb	Whole Group (n=35)		Pre-PHV Group (n=15)		Circa-PHV Group (n=17)	
	R	P	R	P	R	P
SLS R	.926	.000	.934	.000	.929	.000
SLS L	**.807**	.001	.893	.000	.847	.000
SLL R	**.731**	.004	**.937**	.000	.895	.000
SLL L	.866	.000	.898	.000	**.828**	.000

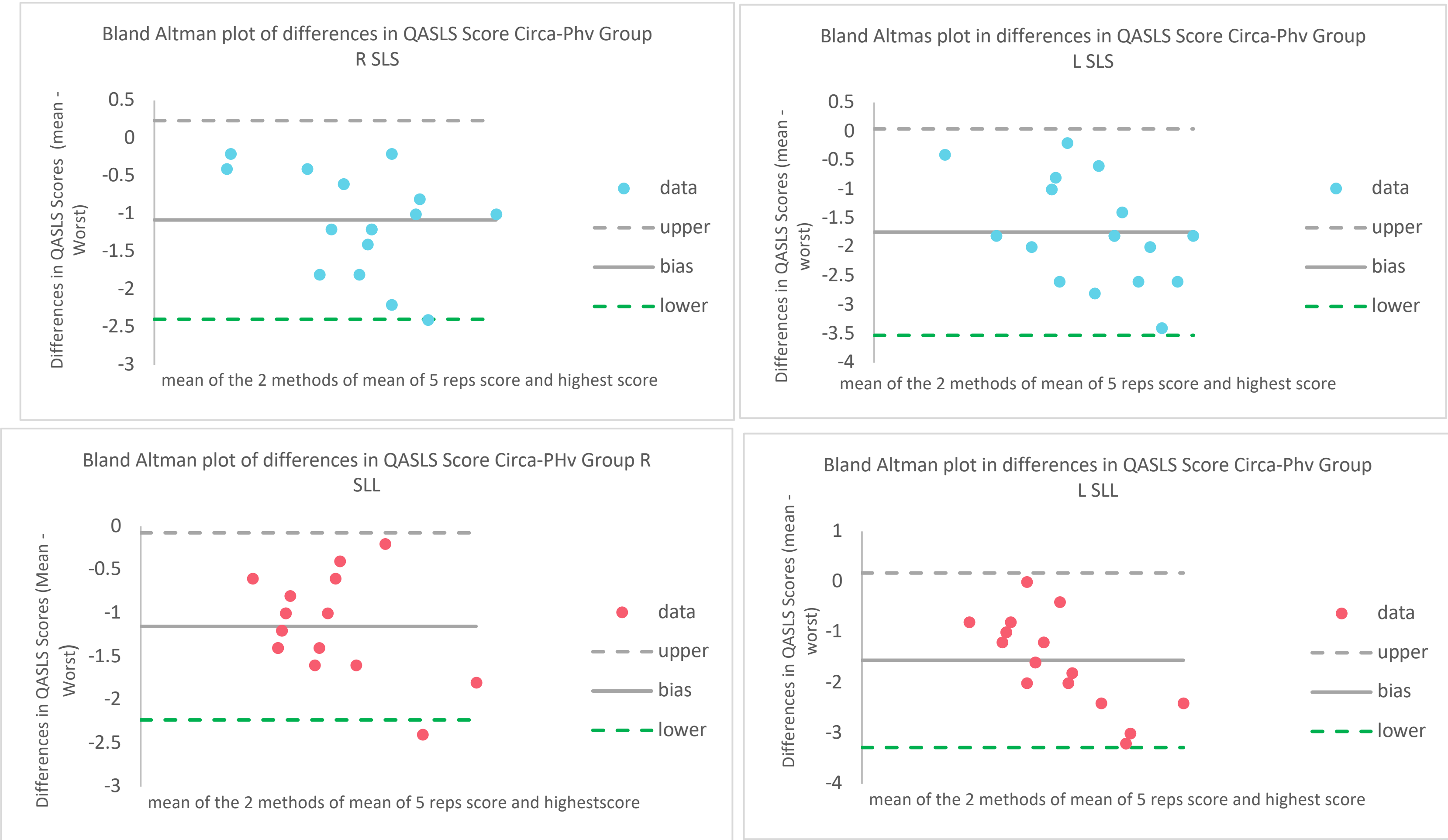
Values in bold denote (R_2) value. Significance set at P = <.05



Figures: 4.3-4.6: Bland-Altman plot of differences of all 35 participants of 2 QASLS calculation methods (mean of the 5 repetitions method minus the worst score method) against the mean of the 2 measurements, by limb and by unilateral tasks. Solid line represents mean between the 2 methods. Dashed lines represent the upper and lower limits of agreement between the 2 methods (±SD).



Figures: 4.7-4.10: Bland-Altman plot of differences of all Pre-PHV group participants of 2 QASLS calculation methods (mean of the 5 repetitions method minus the worst score method) against the mean of the 2 measurements, by limb and by unilateral tasks. Solid line represents mean between the 2 methods. Dashed lines represent the upper and lower limits of agreement between the 2 methods (±SD).



Figures: 4.11-4.14 Bland-Altman plot of differences of all Circa-PHV group participants of 2 QASLS calculation methods (mean of the 5 repetitions method minus the worst score method) against the mean of the 2 measurements, by limb and by unilateral tasks. Solid line represents mean between the 2 methods. Dashed lines represent the upper and lower limits of agreement between the 2 methods (±SD).

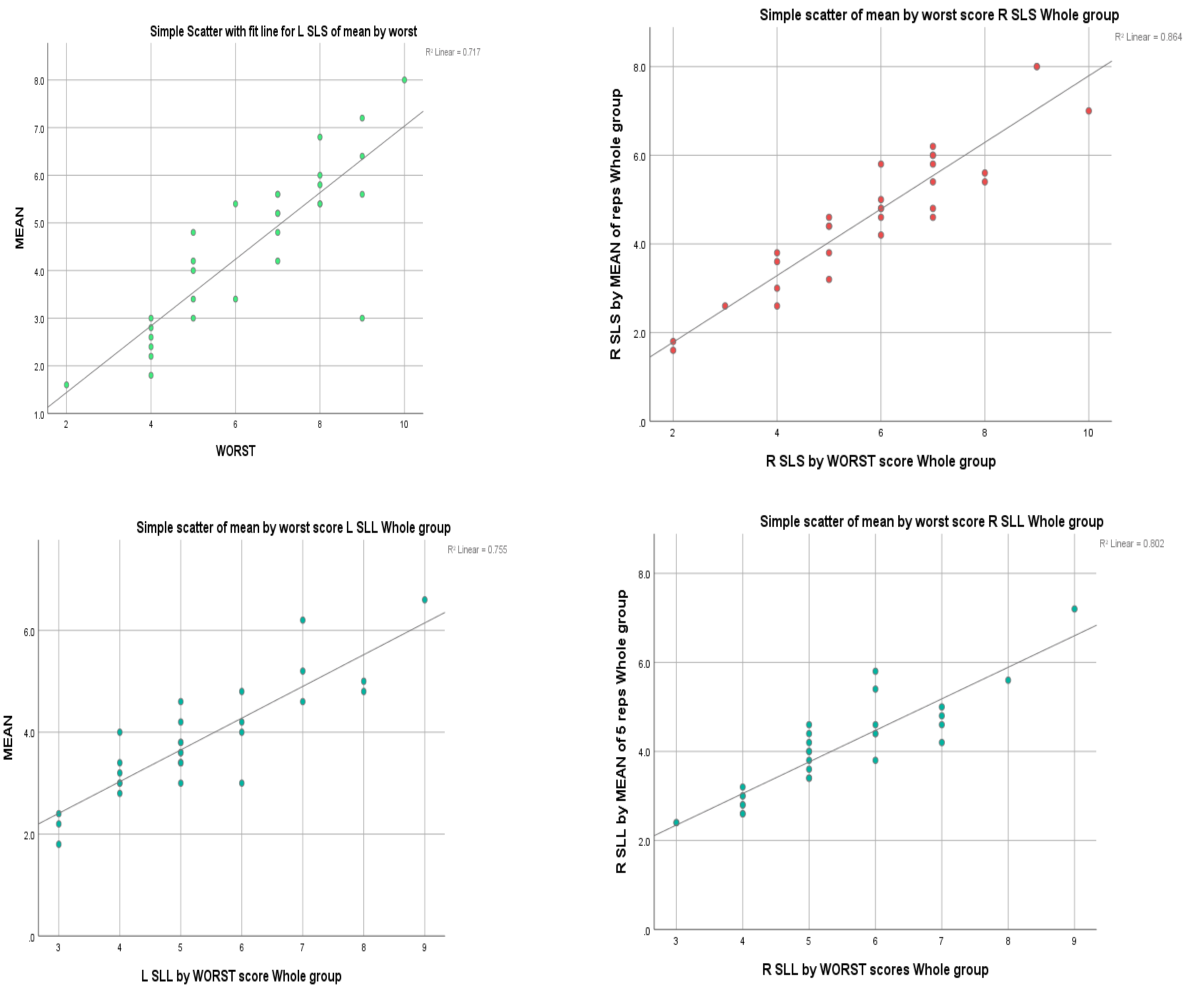


Figure 4.15 Simple scatterplot demonstrating the significant relationship between 2 QASLS score calculation methods for all participants, Right Single leg squat (top left), Left Single Leg Squat (top right), Right Single Leg Land (bottom right) and Left Single Leg Land (bottom left).

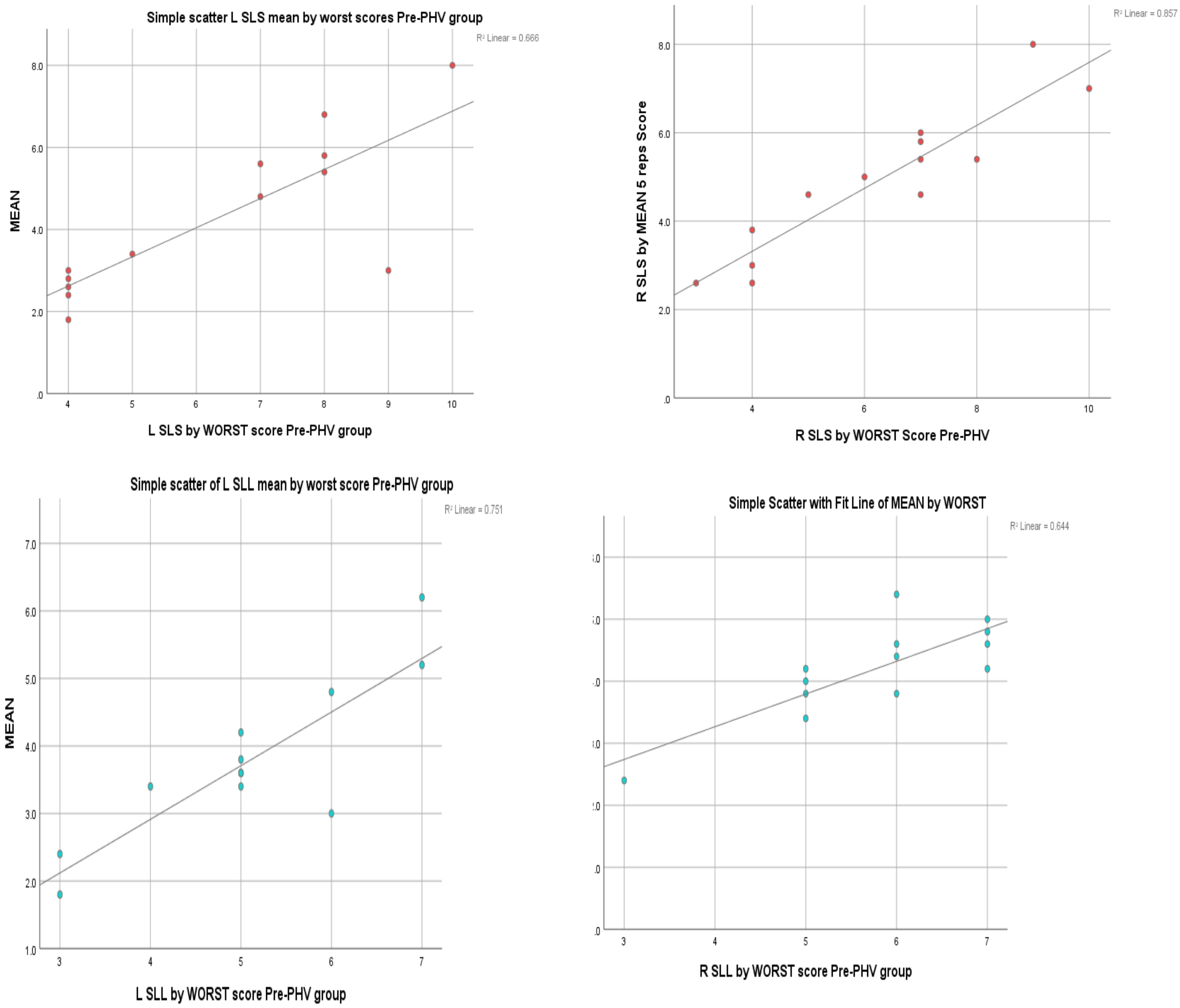


Figure 4.16 Simple scatterplot demonstrating the significant relationship between 2 QASLS score calculation methods for Pre-PHV group participants, Right Single leg squat (top right), Left Single Leg Squat (top left), Right Single Leg Land (bottom right) and Left Single Leg Land (bottom left).

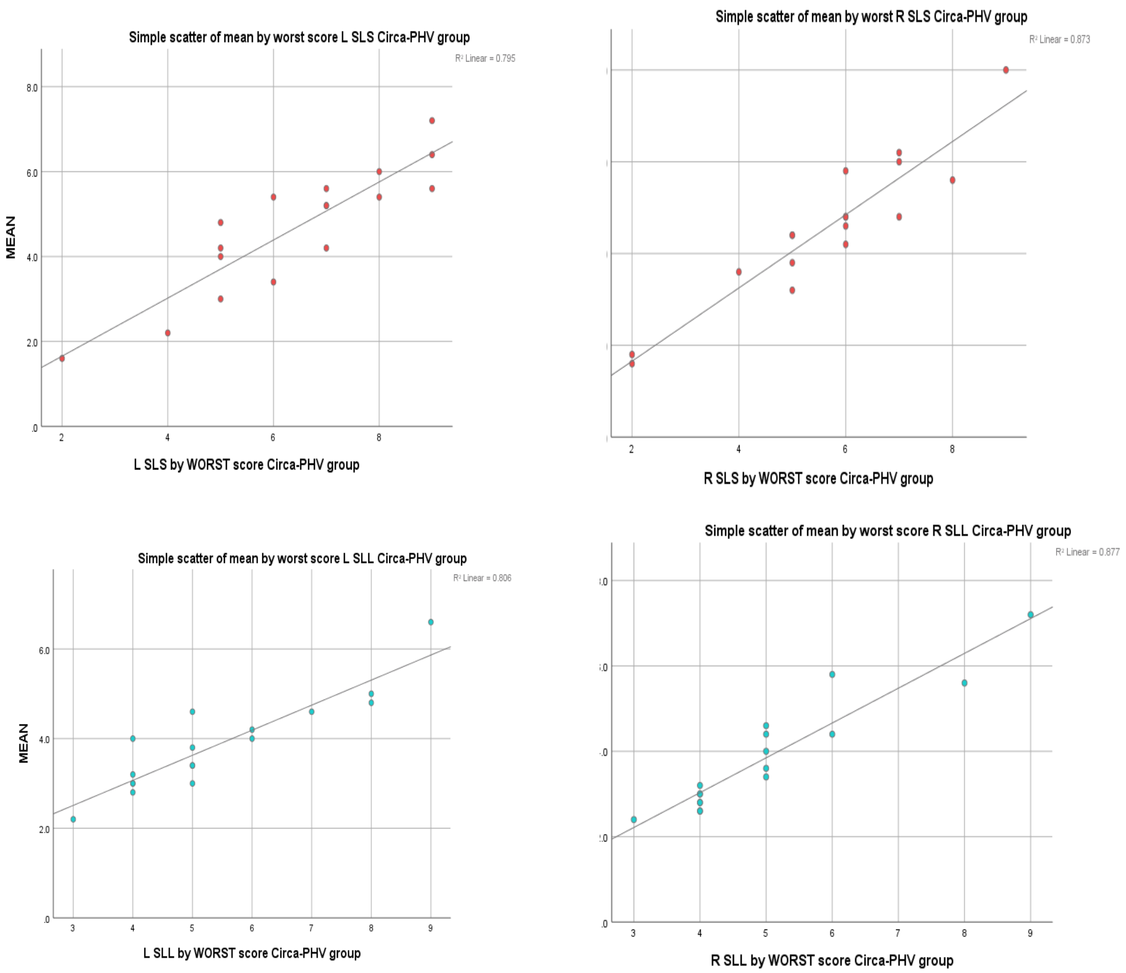


Figure 4.17 Simple scatterplot demonstrating the significant relationship between 2 QASLS score calculation methods for Circa-PHV group participants, Right Single leg squat (top right), Left Single Leg Squat (top left), Right Single Leg Land (bottom right) and Left Single Leg Land (bottom left).

4.4 Discussion

This study focused on the previously identified literature gap of movement assessment within an adolescent population by qualitative means. The potential associations between maturity status and movement quality of adolescents were examined to identify any effects on the 2D kinematic and qualitative QASLS assessment tool established in chapter 3. In addition, the study sought to explore how QASLS scores within this population may differ between calculation methods previously used within the qualitative literature. Within-repetition and between session consistency was evaluated for both unilateral tasks in youth multisport athletes who were assigned to either a pre or circa PHV groups. In relation to the 2D kinematic variables validated in chapter 3, results are as follows, performance consistency between sessions was moderate to good (ICC=0.69-0.81) for trunk variables in the pre-PHV group during both unilateral tasks, there was poor performance consistency (ICC =0.08-0.42) in the fontal plane 2D variables of the LL during landing. Circa-PHV athletes demonstrated poor to moderate (ICC=0.21-0.70) frontal and sagittal plane performance consistency during both unilateral tasks, but good to excellent (ICC=0.88-0.95) sagittal plane trunk consistency during squatting, performance consistency of this variable reduced to moderate (ICC=0.54-0.76) during landing. There was evidence of between task differences by growth group (tables 4.4-4.5), but these were statistically none significant. Within this cohort, there appeared to be a large variation in task performance in both the pre=PHV (6-32.3CV%) and circa-PHV groups (4.9-40.3%CV%). Overall findings of the 2D kinematic variables demonstrated consistent between-session inconsistency, which questions the practical utility of 2D kinematic variables potential in tracking growth-related changes to movement quality.

Similar findings were evident in the qualitative data, with poor performance consistency evident across both calculation methods in the pre-PHV group during both unilateral tasks (tables 4.6 and 4.7). Performance consistency as assessed by compound QASLS score appeared to improve to moderate in the circa-PHV group across both limbs and tasks (ICC=0.50-0.61) but was statistically none significant. There appeared to be a trend of greater movement variation in the pre-PHV group (17.9-40.3CV%) comparative to the circa-PHV group (13-23.9%) during both tasks. Both PHV groups appeared to demonstrate greater performance variation during the unilateral landing task (13.0-29.6% CV%) relative to the unilateral squatting tasks (17.9-30.3CV%). Indicating growth-related task performance differences.

When within-session consistency of the 5 repetitions from 1 trial was analysed, no significant differences were reported between repetitions indicating minimal impact or presences of learning effects. However, two-way interaction analysis of growth group, unilateral task and limb, demonstrated statistically significant difference (p=.042) in between-repetition consistency between growth groups and unilateral task. Further indicating the adoption of different landing strategies by different growth groups when evaluated by the QASLS tool.

When comparing calculation methods of the mean of 5 repetitions and worst score method, it was found that the highest score method leads to increased QASLS scores by at least one mark. When PHV groups were compared on highest score performance, statistically significant differences were present that were not evident in the mean of 5 repetitions method. This provides evidence for the justification of the current highest score method instructions contained within the QASLS tool that is more indicative of an individual's bandwidth of performance. Whilst presenting data as an average of mean scores is frequently common within the sports science literature. It appears that within the context of qualitative assessment, the presentation of a mean score could negate the bandwidth of an individual's performance, resulting in inaccurate interpretation and potential impact on clinical inference. Strong relationships and limits of agreement imply that the worst score method is an appropriate calculation method to be presented by practitioners.

4.4.1 The use of 2D Kinematic variables in an adolescent population

Performance variation for each 2D kinematic variable was large, there appeared to be an overall trend of slightly larger CV% in the pre-PHV athletes compared to than the circa-PHV group during both tasks. Due to the extensive literature documenting the rater-reliabilities (Norris and Olson, 2011; Dingenen *et al.*, 2014; Maykut *et al.*, 2015; Munro, Herrington and Comfort, 2017; Scholtes and Salsich, 2017) of varying 2D kinematic parameters, and the established reliability of method from chapter three, the large variations in movement as assessed by 2D kinematics are likely to be due to participation variation rather than rater issues. Despite the observed differences in between-session consistency of LTL, TFA, HADD and FPPA results were statistically none significant for each growth-group and unilateral task. Several potential reasons could explain the none statistically significant but large performance variations noted in both PHV groups and unilateral tasks.

4.4.2 Isolated 2D Kinematic variables do not appear to provide information on movement patterns as a whole

Within the context of movement quality as a concept, regardless of joint or plane of motion, kinematics is only one aspect of several factors that influence or can be influenced in the way that a movement pattern is executed. Since performance consistency for each kinematic variable demonstrated large variation and was different during wash unilateral tasks, for the ease of interpretation with comparative literature, each 2D kinematic parameter will be discussed individually.

Trunk Lean

The results of this study demonstrate that as a stand-alone measure, variables relating to the trunk in both the frontal and sagittal planes, participant performance between sessions, growth groups or unilateral task are highly variable but non-significant. Out of the small amount of available literature pertaining to 2D kinematic trunk capture, the literature base appears to be limited to rater reliability studies (Chmielewski *et al.*, 2007; Dingenen *et al.*, 2014; Rabin *et al.*, 2014), correlation comparisons to 3D kinematics (Crossley *et al.*, 2011; Khuu, Foch and Lewis, 2016; Schurr *et al.*, 2017), and participants of adult age – or 18 years or older. As between-session consistency remains relatively unexplored the impact of the performance variability of the adolescent participants within this study remains relatively unknown.

LTL was dependant on task and tended to be greater during landing rather than squatting (Tables 2 and 3) as indicated by smaller values. The difference in LTL observed between unilateral tasks is consistent within the findings of Dingenen *et al.*, (2014) who reported that during a single leg vertical jump (SLDVJ) lateral trunk motion was greater than that observed in SLS. As with (Dingenen *et al.*, 2014) elite adult females, it appears the adolescent participants of this study had different trunk position requirements due to the NMC and kinetic chain force transfer differences that occurred during the closed chain squatting and open-chain landing tasks.

The opposite has also been documented in adult females where less unilateral trunk lean during step down tasks compared to SLS has been reported (Lewis *et al.*, 2015). This difference in findings may be attributable to task instruction, as the author justified the difference as a “reflection of the task not a reflection of the participant's ability to control movement.” This confounding factor is further indication that when providing task instruction practitioners need to be highly mindful. Research in the 2D and 3D kinematic domain construct methodologies with very set instructions on how to complete the required tasks that are being evaluated. The participants within (Lewis *et al.*, 2015) paper was instructed in such as way during the SLS and step-down tasks, it is likely that to maintain non-stance leg heel clearance during the task, participants would increase pelvic drop and hip adduction as a means to complete the task. It was also documented that trials where participants who lost balance or used the upper extremities were not included. Similar non-validation of trials where the non-supporting leg touched the ground or participants lost balance or failed to keep their arms across their chest have also been discounted by other authors (Dingenen *et al.*, 2014; Agresta *et al.*, 2018; Dingenen, Staes, *et al.*, 2018). It is possible that those trials where participants might have required trunk lean as a strategy were discounted from the data set as they were considered as a “failed movement”, rather than just accepted as normal variability as they were within this study. Therefore, the variation displayed by the adolescent groups within this study is likely to be a normative magnitude of variation, as the methodological approach regarding task instruction adopted within this study was better placed to capture movement variation rather than discount it.

Another plausible consideration for the lack of statistical difference and high-performance variation between sessions, growth groups, and tasks within trunk measurements, is the concept and structured approach of evaluating a whole movement via one isolated 2D kinematic variable and then trying to formulate conclusions around injury prevention and risk factors from a method that maybe does not fully elude to the wider pattern of the task or the way the task is performed.

Researchers (Dingenen *et al.*, 2015; Scholtes and Salsich, 2017) have attempted to address this gap in the literature by comparing two variables in combination (usually DKV and LTL) in a prospective study for non-contact knee injury risk, and whilst combined DKV and LTL (KVLTM) were significantly smaller in the group that went onto sustain injuries, there was still no significant differences in KVLTM or HF in injured and none injured legs in injured and non-injured groups. It is, therefore, possible that 2D trunk measurements are interdependent on the upper and lower quadrants and that the consideration of a 2D multi-segmental methodology is maybe more advantageous (Dingenen *et al.*, 2015). Although combinations of variables were not compared within this study, trunk position has been shown to influence knee position (Blackburn and Padua, 2008). In this current study, greater trunk lean was required during landing tasks than those observed during squatting, and further highlights the interdependency of body segments and the impact interactions within the kinetic chain have on the variability of a movement pattern. Movement pattern variability is highly likely to be resultant of what occurs at a singular or a couple of joints, these findings, therefore, acknowledge the limitations of trunk lean when presented as an independent variable and support the analysis and consideration of relationships around the multi-segmental approach.

Trunk Flexion Angle

When considered from the sagittal plane trunk values were also smaller during landing (27-31°) compared to SLS (42-45°) suggesting that participants adopted a more flexed trunk position during landing tasks. Sagittal plane variables, notably of the trunk are regularly identified as contributors to multiple knee pathologies (notably PFP and ACL) (Zazulak *et al.*, 2007; Hewett, Torg and Boden, 2009; Dingenen *et al.*, 2015; Bakker *et al.*, 2016; Scattone Silva *et al.*, 2017; Schurr *et al.*, 2017), whilst many authors have documented trunk flexion as a risk factor variable (Dingenen *et al.*, 2015) it remains highly elusive with other authors demonstrating no difference at all (Leppänen, Pasanen, Krosshaug, *et al.*, 2017b). In their multivariate regression analysis to establish correlation sagittal plane kinematic/kinetic variables to ACL strain during landing, Bakker *et al.*, (2016) deduced that combined lower limb angles and ground reaction force during landing where a better predictor of ACL strain comparable to when the variables were presented in isolation. In addition, the contribution of kinematic factors compared to the contribution of non-modifiable anatomical factors were negligible. These findings are consistent with the non-significant differences in performance in this study and further highlight the limited utility of reporting 2D trunk kinematics as stand-alone variables.

Hip adduction angle

Hip adduction angle demonstrated no significant difference in performance between sessions and similar values between limbs and tasks. Current studies that evaluate hip adduction angles are also limited to rater-reliability (Almangoush, Herrington and Jones, 2014; Barker-Davies *et al.*, 2018), it appears to date that no papers have analysed participant variability or differences between test occasions. It is therefore difficult to make exact comparisons to the results of this study. 3D hip and knee kinematics in healthy active women have also documented difference in reported hip adduction that are statistically none significant in poor and good performers (Hollman *et al.*, 2014). There were also no notable differences in knee kinematics or additional hip markers between their groups. Whilst the authors went on to suggest that their findings did partially support their hypothesis that there would be between-group differences, due to the difference in values and reported correlations between hip kinematics and knee valgus, they did acknowledge that using several movements to analyse squat performance was likely to be more objective adding further weight to the rational that stand-alone kinematic parameters provide very limited information. Although the paper did not offer suggestions to explain the non-significance of results, it is possible that for the adult female participants, like the adolescent participants in this paper, when analysing hip adduction as a singular marker large variation in performance will be noted. It is likely therefore that due to the multiplanar nature of movement tasks, numerous patterns occur to complete the same task, and singular joint evaluation at singular time points does not lend itself to establish statistical significance.

FPPA

The DKV mechanism has long been described as an "aberrant" movement pattern for a variety of knee ligamentous and intra-articular pathology (Scattone Silva *et al.*, 2017) and resultantly there is extensive literature citing significant differences in varying population groups and genders (chapter two). The results of this research appear to be in contract with the literature with reported FPPA values demonstrating statistically non-significant limb differences (tables 4.2 and 4.3). Statistically insignificant performance variation with measurement consistency has been determined in 2D and 3D FPPA measurements during bilateral landings (Mizner *et al.*, 2012), and more recently in pathological groups (Räisänen *et al.*, 2020), and runners (Rees, Younis and MacRae, 2019). It is therefore likely that kinematic and kinetic measurements of knee valgus are potentially one aspect of multiple independent predictors. The high-performance variability and impact of other segmental regions could provide a possible explanation of why no significant differences were detected between session FPPA performance. Generally, the results of this study are in contrast to the common supposition that 2D kinematics are pragmatic for whole movement analysis. In fact, this data further highlights the multiple strategies of movement that participants use (evidenced by the variation of performance), and that participants change combinations of the way that they use multiple parameters. It is unlikely therefore that 2D movement assessment can be fully detected by analysis of a singular kinematic variable as too few participants ever select the same strategy for the mean difference to be statistically recognized.

4.4.3 Maturational status influences the variability of 2D kinematic variable performance

Pre and circa PHV groups appear to present different kinematic values during the SLS and SLL. The pre-PHV athletes seem to use different SLS strategy as demonstrated by smaller trunk values along with large hip adduction angles, suggesting that during squat tasks the pre-PHV group used more trunk range and less hip adduction than their circa-PHV counterparts. This changed during the landing task where the circa- PHV group also presented smaller trunk values and larger hip adduction angles than during the SLS, indicating that circa-PHV adolescents use more trunk and less hip adduction for landing than they do for squatting. Conversely, both PHV groups presented with similar FPPA values during each task, with each demonstrating smaller values and less DKV during landing than squatting. This disparity between the difference in 2D values between tasks, PHV-groups and statistical significance may be attributed to the influence of maturation on specific tasks, during growth previous research has indicated that frontal plane lower limb alignment is not the product of a single joint but composed of multiple movements from ankle inversion or eversion, knee valgus, hip internal rotation and adduction (Padua *et al.*, 2009; Powers, 2010; Gwynne and Curran, 2014).

Although generally limited to cross-sectional designs and the reporting of knee variables, previous studies (Paz *et al.*, 2016; Räisänen *et al.*, 2018; Collings *et al.*, 2020), differences in 2D kinematics across tasks and sports have been associated with growth and maturational changes. Greater FPPA values have been noted during DVJ compared to a step-down test in 13-year-old volleyball athletes. In adolescent footballers, FPPA performance evaluated by gender was statistically non-significant, when the same data was presented by chronological age, FPPA performance values improved with age with better FPPA values recorded in the older cohorts (Räisänen *et al.*, 2018a).

This point has been further contended in competitive youth and elite alpine skiers (Ellenberger *et al.*, 2020). Ellenberger *et al.*, (2020) where DKV was directly associated with an individual's biological maturational status and values for unilateral squat tasks were nearly double those encountered during bilateral landings. Statistically, none significant gender differences in MKD were evident in those in the U15s age group, however, those differences were no longer evident in the elite group who had already completed their maturational process. These differences in kinematic knee displacement are therefore likely to be representative of maturational status than gender.

In addition, trivial non-significant similar KV and hip internal rotation angles results have been documented in young female netballers (age 15-25) (Collings *et al.*, 2020). Collings *et al.*, (2020) demonstrated no statistical significance in frontal plane knee control between elite and non-elite group netballers. As task and gender were controlled for, the lack of statistical difference may have been explained by the average age of the participants. The elite group averaged 17 ±1.7 and non-experienced group 22 ±3.2 years, it is highly likely that their maturational process would have been completed and therefore any differences due to maturation in knee kinematics would have equalised.

Additional research to compare performance variation in 2D kinematics in different adolescent PHV groups is limited. Cumulatively, the current study findings of large performance variations in each 2D kinematic variable between PHV groups and the unilateral tasks themselves provide a further rationale that growth and maturation affect task performance within an adolescent multisport performance setting. Results also highlight the potential limitations to the drawing of meaningful conclusions when movement analysis is limited to the lens of a single kinematic parameter, as practitioners focusing on one kinematic variable in isolation within a whole movement pattern, misinterpretations may be made. However, in the same way, that trunk position, hip adduction or knee valgus are only one of several variables that represent elements of a bigger picture of movement quality, maturity status is potentially only one of several other factors that specifically influences movement quality performance, consideration of just one variable, all be it kinematic or growth-related is likely to produce very mixed results.

4.4.4 Movement quality appears to comprise multiple confounding factors

Individual participant performance of 2D kinematic variables by an adolescent population appeared consistently inconsistent, as evidenced by low ICC and high coefficient of variation (CV%) values. When analysing between session performance, ICC retest correlations monitor the extent to which individuals keep their rank order in repeated measurements (Hopkins, 2000; Liljequist, Elfving and Roaldsen, 2019). The low ICC values of the participants in this study indicated that pre and circa PHV athletes did not retain their rank order. The pre-PHV group exhibited less consistency in frontal plane hip and knee variables (ICC=-0.25-0.68) than the circa-PHV group during both unilateral tasks, but greater consistency at the trunk in both the frontal and sagittal plane (ICC=0.69-0.82).

Younger children tend to struggle with the calibration of postural stability during more challenging postural tasks and anterior-posterior directions (Quatman-Yates *et al.*, 2012). In relation to motor skill performance, pubertal children follow an anticipated and fundamental sequence (Difiori *et al.*, 2014), moving the body as a whole unit rather than discerning a coordinated segmental approach (Vallis and McFadyen, 2005). During the growth spurt individual's growth velocities are highly varied (Cumming *et al.*, 2017). Development of the musculoskeletal, ligamentous and connective tissue system is asynchronous, in combination with a potential lag in the sensorimotor systems governing proprioception, some adolescents show a persistent improved ability to decouple body segmental movement (Saavedra, Woollacott and Van Donkelaar, 2007), and others developing regressions or plateaus (Loko *et* *al.*, 2000). It is possible that the younger pre-PHV athletes in this study, due to their developmental phase, presented performance values that were more closely clustered and widened the chances of changing rank order. It was likely the circa-PHV group had greater performance variation within the developmental phase due to the non-linearity of the growth process, and therefore performances of the unilateral tasks were less likely to be clustered and rank order less changeable and more established.

The CV% is a means of assessing variability through the expression of a percentage of consistency, presenting a practitioner with an idea of where within the observed scores and error range between trials, the true score of a participant lies (Turner *et al.*, 2015; Bishop *et al.*, 2018). Although subject to conjecture, within the sports science literature an arbitrary cut off value of 10% or below has generally become accepted (Atkinson and Nevill, 1998). The majority of the literature has concluded this from previous biomechanical papers that have reported reliability within the vicinity of 10% (Cormack *et al.*, 2008) of methodologies for individual biomechanical variables, not variable performance consistency.

Frontal plane FPPA (CV% 18-40), and frontal (CV% 10-16) and sagittal (CV% 14-22) trunk angles in both PHV groups were found to lie outside the suggested CV% limits, and as such is noteworthy as this suggests these are the body segmental regions where adolescent multisport athletes will demonstrate the most performance variability. The CV% ranges reported within this study are reflective of those reported in earlier biomechanical research, where during vertical jump performance larger CV% values of 13.4-18.3% were accepted as valid and reliable (Aragon-Vargas, 2000). More recently, higher CV% values of 10-15% when assessing peak GRF asymmetry during CMJ (Bishop *et al.*, 2018) have also been deemed as valid. Ultimately it is up to the individual researcher to determine CV% application, it is likely when considering performance consistency within a youth population that CV% below 10% do not adequately reflect performance variability for most 2D kinematic variables. With that in mind, when the goal of CV% is to denote human performance variability, not methodological reliability, practitioners may wish to consider high CV% values as acceptable.

4.4.5 2D Kinematic variables summary

In summary, despite differences in reported values, moderate to poor ICC values, high CV% and absence of between-session statistical significance, suggest that the performance of unilateral squatting and landing tasks by adolescent multisport athletes, as assessed by 2D kinematics are relatively inconsistent. There appear to be trends in maturational groups with pre-PHV athletes demonstrating greater variations and larger ranges of 2D kinematic variables than circa-PHV athletes. When evaluated by multiple 2D kinematic variables landing tasks also appear to demonstrate greater variations in performance than squatting tasks across both PHV groups. The data set indicates limitations of whole movement pattern evaluation by individual 2D variables. As isolated 2D variables appear to represent only a segment of a total movement picture, practitioners wishing to evaluate whole movement patterns, or track whole movement performance changes overtime, must be aware of this limitation.

4.4.6 QASLS Score in a Youth Population

When comparing pre and circa-PHV athletes during both unilateral tasks between-session performance consistency over a three-week period was largely varied but statistically none significant. Across both tasks and limbs, CV% of compound QASLS scores was high, indicating large variability in movement patterns, especially within the younger pre-PHV cohort. Whilst the large variations in performance potentially explain high CV% and none statistical significance, they also lend support to the rational that circa-PHV groups are more likely to present less performance difference than pre-PHV athletes and retain their rank order due to variations seen within the growth spurt period. When comparing compound QASLS score methods, of both unilateral tasks, conversely there was no significant difference between sessions when the mean of the 5 repetitions method was used, but when performance was evaluated using the highest score method significant difference was established. This is similar to the research of (Agresta *et al.*, 2017), who when visually assessing SLS performance in 8-17-year-olds, did not see significant performance differences by gender, but did see significant trends in poorest performance, especially in the youngest most immature group.

Whilst measurement of repeated, rather than single effort repetitions of a task increases variable reliability, the consequence is the diminishment of performance bandwidths as high or low scores become less prominent (Cormack *et al.*, 2008). Within clinical practice, a single effort will rarely be analysed. Understanding of athletes lowest and highest scores within an average maybe more insightful to practitioners particularly those involved with mitigating against injury risk as it provides greater insight into an individual's movement bandwidth and performance capabilities. Due to these findings, calculation methods were analysed further and additional information is reported in section 4.4.8. This is particularly pertinent within a youth population where any movement assessment tool needs to be capable enough to keep up with the rate of change of the growth and maturational process.

4.4.7 Maturational status influences QASLS compound score

Between-repetition consistency of QASLS compound score was not statistically different in either PHV group. Ranges of scores were highly varied, with more variation noted within the pre-PHV group. This suggests within group; performance of unilateral squatting and landing tasks remains decidedly individualistic. Whilst the absence of statistical difference between each repetition suggests there were no learning or familiarisation effects, there is a lack of commensurable literature to compare these findings to. This appears to be the first study to consider between repetition differences of QASLS scoring, and qualitative movement analysis tools in general, as there does not appear to be any other papers pertaining to learning effect in other qualitative tools such as the LESS, FMS or TJA. Learning effects within the dynamic lower limb control test SEBT, have been shown to stabilise after four trials (Robinson and Gribble, 2008; Munro, Herrington and Comfort, 2017) suggesting the five repetitions used within this should have been enough to explore any QASLS test differences that could have been associated to a learning effect.

Intriguingly, the highest QASLS scores were statistically different between PHV groups during the squatting and landing tasks. Given the lack of apparent variability across the 5 repetitions within PHV groups, indicates that the between PHV group are likely to be attributed to the effects of growth. During periods of rapid growth, it is anecdotally reported that children and adolescents demonstrate changes in movement quality that are suggested to be caused by changes in the sensorimotor mechanisms, these changes are frequently referred to as "adolescent awkwardness." (Quatman-Yates *et al.*, 2012; Agresta *et al.*, 2017; Cumming *et al.*, 2017). Whilst many practitioners refer to the phenomenon and it is commonly accepted term throughout sports science disciplines and practise, research around the adolescent awkwardness concept regarding identification and measurement remains highly limited and elusive. The motor awkwardness theories attributed to growth have evolved on the assertions that NMC and proprioceptive ability are impacted by changes in cortical mapping information processing, and physical rapid changes in the centre of mass, proportions of body segments and intersegmental coordination (Quatman-Yates *et al.*, 2012; Wild, Munro and Steele, 2015; Cumming *et al.*, 2017).

The distinct lack of data relating to the adolescent sensorimotor function and limited understanding of its relationship to injury risk (Quatman-Yates *et al.*, 2012) make suppositions on this subject somewhat anecdotal. The statistically significant interactions between growth groups and tasks in this study tentatively support the adolescent awkwardness assertions. SLL performance significantly improved with age, with pre-PHV athletes demonstrating higher QASLS scores, and thus the requirement of more strategies than the circa-PHV athletes to complete the same task. Many younger children struggle with appropriate task-specific volitional muscle tension, uncoupled segmental movement patterns and postural adjustments (Quatman-Yates *et al.*, 2012; Whatman, Hume and Hing, 2013; Lester *et al.*, 2017). Therefore, they may require the use of additional body segments and strategies (such as upper limb or ankle) before maturation of sensorimotor mechanisms, which was evidenced in this study by a greater QASLS score. Many practitioners involved with adolescent athletes report regressions and alterations to previously unimpeded movement patterns around the time of growth (Hewett *et al.*, 2005; Quatman-Yates *et al.*, 2012; Difiori *et al.*, 2014; Wild, Munro and Steele, 2015; Cumming *et al.*, 2017; Myburgh, Cumming and Malina, 2019), and therefore "adolescent awkwardness" is considered to be an injury risk factor unique to the adolescent population. This has important clinical implications for practitioners, whilst the data does not provide understanding into specific aspects of sensorimotor function, it suggests that total compound QASLS score and the movement variation in strategy evidenced by the repetition analysis, has the potential to demonstrate changes in overall quality of unilateral movement patterns relative to the phase of growth.

4.4.8 Differences in QASLS score calculation methods in a Youth population

The authors that conceived the QASLS system (Herrington, Myer and Horsley, 2013), suggest that it can be used to analyse a single unilateral effort or a series of efforts across both squatting and landing tasks. The authors devised a dichotomous system over 10 components that results in a compound score of 0-10. The 10 components that comprise the compound score are allocated a zero for an appropriate strategy and a one for an inappropriate strategy. There are no definitive instructions regarding QASLS score calculation method for more than 1 repetition. For athletes completing more than 1 repetition, anecdotal reporting suggests that if a strategy is observed on any repetition regardless of if observed on just one repetition or all five, a participant receives a one, with the highest score being recorded. Within the sports science literature, studies analysing kinematic or kinetic variables calculate the scores of an individual as an average across multiple trials (usually 3 or 5) (Hanzlíková, Athens and Hébert-Losier, 2020).

Due to this, two different calculation methods of the mean of 5 repetitions and the highest score methods were compared as these are the most common calculation methods of QASLS scoring used in current clinical practice. The mean score of the 5 repetitions was considered as the reference method as this is the most common method presented in the literature evaluating other qualitative tools (Fort-Vanmeerhaeghe *et al.*, 2017; Hanzlíková, Athens and Hébert-Losier, 2020). Following the comparison, the highest score method led to higher QASLS compound scores by 1.5 for the pre-PHV group and 1.3 for the circa-PHV group, SEM values established in chapter 3 for within-session reliability are 0.45-0.89 which suggests the differences noted from the highest score method are clinically relevant, and could ultimately impact application and clinical perceptions.

By reporting an individual's compound score a practitioner can gain an understanding of the number of strategies an individual needs to deploy to complete a fundamental task and as such reflects their whole performance system. By reporting their "highest" score (or the number of strategies to complete the task) may a better way to inform practitioners around potential factors or strategies of risk, which may otherwise be diminished in the average of multiple trials method.

Human movement remains highly variable, as demonstrated by the data presented in this chapter, and having a tool that can keep up with the assessment of movement quality in a non-linear way is highly important. Whilst critics have condemned the reporting of a single repetition or variable on the grounds that it is unable to epitomise an individual's pattern of movement (Sands *et al.*, 2019) the highest score method suggested within the QASLS tool should negate the possibilities of capturing an atypical performance.

Data suggests the mean of the 5 repetitions calculation method is representative of an individual's average movement pattern, and the highest score calculation method eludes more to a bandwidth of an individual's movement pattern. Practitioners should be aware that different calculation methods of QASLS scoring provide contrasting information that might impact clinical inference. Obtaining a mean score of 5 repetitions is recommended to report on general movement pattern performance, the conclusion of a higher score method should be included to report on the variability of the movement pattern performance. In terms of the practical application of QASLS scoring to unilateral task performance, understanding an individual's movement variability provides practitioners with information around the options of movement that are available to them. A practitioner can then decide based on the individual's context if the observed variability is optimal or suboptimal for the movement pattern demands an athlete is facing. By using the QASLS tool in a nonlinear way to understand movement variability, practitioners, in turn, will be better placed to understand the interactions of the kinetic chain, the movement complexity, and any impact this may have on injury risk. Secondly, the relationship between calculation methods was strong. If a practitioner is limited in time, results in this study demonstrate that multiple repetitions maybe evaluated in one higher score as a viable alternative to scoring individual repetitions of a multiple set.

4.4.9 Strengths and Limitations

There are potential limitations within this study that require consideration within the study's findings. Within this work, 2D variables have been considered in isolation as singular parameters. Whilst similar to the current consensus around 2D methodology, the data set has demonstrated the limitations of isolated variables in representing a holistic global picture of a movement. Multiple 2D variables from two movement planes were measured and reported, however, combinations of the 2D variables were not. It might be possible that a combined variable evaluation reflected the component skills or movement constructs differently, however, the none significant findings between tasks, limb and PHV groups are informative and evidence enough to discontinue further evaluation of the isolated method within a whole movement pattern.

Although common within the sports science approach, the second limitation of this current study is its cross-sectional design. Only information pertaining to compound QASLS scores in two growth groups on two occasions were presented in this study. Participants performances were only captured twice and their growth status analysed once. The application of these results is therefore limited to this period of time, and may not be fully representative of QASLS scores across a season or a year of an athlete's development process. Due to the absence of longitudinal data, it is difficult to conclude if QASLS scores would change over longer periods of greater than a month, and as such the discussion is comprised of previously identified theories around growth, maturation and movement quality. Cross-sectional designs are built on inflexible approaches that linearly assume progression or regression, this approach might be limited in capturing the non-linear progression and regression that adolescents may experience during growth. The data suggests that the QASLS profiling tools can be used effectively to capture movement quality of two unilateral tasks, with consideration of the context of maturational status. It is likely that the findings regarding clinical utility of the method could be incorporated into a future longitudinal research design that can track athletes over a period of time to address some of the limitations of the cross-sectional methods.

Due to its frequency of use within professional and academic practise the average of 5 repetitions method was selected as the method to evaluate and measure the highest repetition method against. Despite its frequency of use and universal acceptance in practice, there is no real precedent as a true reference method. However, the purpose of this section was to establish the differences and potential limitations between calculation methods based on current QASLS scoring and its current use in practice, and therefore this should not hinder interpretation of this studies results.

Within this cohort, the majority of participants classified into pre and circa-PHV categories as only three participants (two male, one female) classified into post-PHV group, meaning there was limited opportunity for comparisons across all phases of growth and sex. Drawing on a larger more varied participant sample may assist with the clustering of participants into certain growth categories, and should be considered to allow for the further interpretation between the effect of sex, profiling and movement quality. Following on from clinical utility perspective this would help discern differences between biological-sex-specific strategies and gender-specific impacts on performance.

5.0 Conclusion and Practical Applications

Performance of two unilateral tasks by youth athletes across a three-week period when evaluated by 2D parameters and QASLS methods appear to be largely varied and inconsistent. 2D parameters are practically feasible for clinicians, but the isolated evaluation within the approach does not translate into the whole movement pattern. The variability reported in these results suggests that an adolescent individual's movement pattern will be driven by numerous factors and not just by one variable. In terms of performance implication, it is highly unlikely that a change in one kinematic variable will hugely impact performance. 2D kinematics appear to evaluate one thing multiple times, systems such as the QASLS tool that can analyse an athlete as a complex system, and identify the relationships between components attributing to the collective movement pattern is likely to be more useful. Total compound scoring can provide practitioners with a more holistic picture of the whole system, that allows whole system variability to be evaluated. The presentation of 2D variables and average QASLS scores in isolation is insufficient to demonstrate significant differences in this multisport adolescent group during both unilateral tasks. However, when the highest score method and variability were considered, PHV-group differences in task performance were observed suggesting neuromuscular changes in movement patterns during growth. It is recommended when considering a youth population inclusion of biological maturation or developmental stage is crucial. Indeed, the highest score method demonstrates greater clinically applicability especially for performance and potential risk evaluation. Longitudinal approaches to research design will help close knowledge gaps around movement quality in youth populations concerning a competitive season or developmental stage, previous research regarding movement quality has tended to focus on isolationist variables, this work has applied a qualitative combined systems approach that has greater potential for practical application.

Chapter 5

5.0 A seasonal evaluation of qualitative performance of two unilateral tasks in adolescent athletes.

Acknowledgement

I would like to acknowledge Sarah Henderson for her part in the data collection analysis process of this chapter

5.1 Introduction

Adolescence has been identified as a period of magnified injury risk particularly in children aged 10-14 that compete in sport at both the recreational and elite level (Quatman-Yates *et al.*, 2012). The number of younger children and adolescents involved in sport is existentially on the rise (Rejeb *et al.*, 2017) and injury epidemiology within the young elite population still emerging (Von Rosen, Kottorp, *et al.*, 2018), tools and tasks that can capture the neuromuscular elements of movement quality relative to injury risk are important.

It has been inferred that factors that attribute to injury and injury risk are similar for youth athletes to those seen in the adult population. Whilst injury risk factors may be similar, injury occurrence and potential variation in the seasonal influence of modifiable and partially modifiable risk factors in youth athletes are not (Waldén, Hägglund and Ekstrand, 2005; Pfirrmann *et al.*, 2016).

This is an important delineation to make, as the mitigating strategies to combat associated seasonal variation and injury risk within an adult environment may not necessarily apply in the same way at the same time within an adolescent youth population. Due to the lack of literature pertaining to profiling within the youth population, there is a risk that scaled-down versions of adult profiling may be applied as most data is currently drawn from the adult elite. In the same way, training load programmes are starting to be tailored to the adolescent athlete, profiling interventions should be approached in the same way to account for the unique requirements of this youth population.

There are very few prospective studies that analyse injury incidence concerning the time of year in youth populations. Jespersen *et al.*, (2014) reported that seasonal variation in MSK (musculoskeletal) injuries in children aged 6-12 years were clearly evident, with a 46% increase in injury incidence during summer compared to the winter. The prevalence of summer injuries has also been shown in UK School children presenting to the Accident and Emergency department (Graham, MacDonald and Stevenson, 2005). Lloyd *et al.*, (2020) obtained results suggesting the reduction of neuromuscular control (NMC) in youth male footballers over a competitive season. During the adolescent growth spurt, youth athletes can experience rapid changes in centre of body mass, limb length and moments of inertia (Difiori *et al.*, 2014), with some athletes also experiencing transient changes in co-ordination, postural and neuromuscular control (Quatman-Yates *et al.*, 2012). These changes to the sensorimotor systems, notably NMC have been proposed to increase injury risk in adolescents due to the impact on the movement patterns of sporting and non-sporting tasks (Difiori *et al.*, 2014).
Altered NMC may therefore be a contributing factor to the seasonal variation of performance tasks, as developing athletes adjust to rapidly changing bodies whilst also delivering and performing highly complex sports performance tasks.

The seasonal variation of increased summer injuries usually coincides with the pre-season or season start for the majority of sports, as well as the start of the academic school year in the UK. Due to this, there have been many proposed explanations around extrinsic factors such as the weather, harder firmer playing surfaces (Jespersen *et al.*, 2014), and intrinsic factors such as age, response to load exposure, recovery status, fatigue and NMC (Pfirrmann *et al.*, 2016; Hopper *et al.*, 2017; Lehnert *et al.*, 2017; Rejeb *et al.*, 2017). However, a recent prospective study in Spanish youth footballers demonstrated that injuries followed specific patterns according to the percentage of adult height, not necessarily seasonal variations occur (Monasterio *et al.*, 2020). Further identifying a potential association between maturation and movement quality as an injury risk factor for adolescent athletes.

Athlete maturation is asynchronous, progresses at different paces and times between individuals (Cumming *et al.*, 2017), and therefore it remains unclear if seasonal injury variation reflects maturational changes that are occurring during a sporting season, or maturation is impacted by changes in seasonal extrinsic risk factors. The majority of MSK injuries, regardless of if they are in adult or youth population remain multifactorial and the issue of seasonal variation is likely to remain highly complex.

Sex-specific biological differences are evident throughout the adolescent growth spurt (Malina *et al.*, 2015; Parsons, Coen and Bekker, 2021), what is now less clear is if gender related differences truly appear biomechanically. Females have been shown to demonstrate differences in knee and hip angles and moments during various landing tasks compared to males (Hewett *et al.*, 2005; Noyes *et al.*, 2005; Ford, Myer and Hewett, 2010; Wild, Munro and Steele, 2015). However, within this previous body of literature, measurement of classification of participants by maturity statue has not been fully considered. Conversely, more contemporary literature (Ugalde *et al.*, 2015; Agresta *et al.*, 2017; Räisänen *et al.*, 2018a; Ellenberger *et al.*, 2020) has reported no significant differences in biomechanical variables of unilateral movement patterns between gender groups, but have reported significant differences in movement performance in both genders as a result of maturational status (Agresta *et al.*, 2017; Räisänen *et al.*, 2018a; Ellenberger *et al.*, 2020). Conclusions from these studies regarding sex-specific mechanical performance differences appears contradictory, and alongside a changing narrative regarding the general concepts of wider influences on gender-specific performance differences beyond physiological and biomechanical cause (Nimphius, 2019; Fox *et al.*, 2020; Parsons, Coen and Bekker, 2021), the conclusive influence of gender on mechanical performance remains unknown.

For a large proportion of youth athletes, entry into sports participation is happening at younger ages and more intense levels. Many children and adolescents are involved in multiple teams, compete in multiple tournaments that result in year-round training (Brenner *et al.*, 2007, 2016; Cumming *et al.*, 2017; Pasulka *et al.*, 2017) which can contribute to overtraining and burnout (Brenner *et al.*, 2016; Murray, 2017; DiCesare, Montalvo, Barber Foss, Thomas, Hewett, *et al.*, 2019) changes in NMC and movement quality (Ellenberger *et al.*, 2020; Lloyd *et al.*, 2020), and a reduction in performance, as adaptation and recovery opportunities become limited.

For these reasons, exploration around the longitudinal monitoring of performance markers throughout a school year or sporting season will inform appropriate understanding around their application with adolescent cohorts to successfully determine variations that may be associated with periods of reduced performance and fluctuations in injury risk. When it comes to youth adolescent athletes, data sets around variation in performance throughout a season are small and frequently ingrained within the monitoring of training load, or singular biomechanical kinematic or kinetic parameters (Towlson *et al.*, 2020).

Although mainly restricted to the sport of football, limited papers documenting seasonal variations in performance variables in the adolescent youth population, changes both positive and negative in varying physical qualities (such as speed, power, strength, aerobic, hop and CMJ) have been observed pre and post-season (Rousanoglou, Barzouka and Boudolos, 2013; Read *et al.*, 2016; Saward *et al.*, 2016; Morris *et al.*, 2018; Emmonds *et al.*, 2020). Longitudinal age-related changes in match running distance during competitive football matches over 3 seasons in 263 elite youth male players has been assessed. Total distance ran and sprinting efforts all changed with age throughout the season in a non-linear manner, with significant performance variation between players of the same age (Saward *et al.*, 2016).

Additional papers (Morris *et al.*, 2018; Emmonds *et al.*, 2020) have included further performance variables, specifically around speed, change of direction (COD), aerobic capacity and isometric leg strength, showing links between seasonal change and changes in physical performance. Variables were monitored over a season with data collection occurring at its start (September) and end of the season (May) in 112 male football players and 38 adolescent controls (Morris *et al.*, 2018). Compared to a control group, only elite circa-PHV players demonstrated improvements across all physical qualities. Pre-PHV players demonstrated increases in sprints, COD and CMJ variables, whilst those in the post-PHV group only demonstrated COD and isometric strength changes between pre and postseason. The authors expressed huge independent variability in performance and non-linear changes in trends notably in speed that they attributed to the role of growth and maturation.

In a similar study (Emmonds *et al.*, 2020) in an elite youth female football cohort, that examined almost identical strength, COD, CMJ, speed variables, but at pre, mid and post seasonal points. Changes were shown in variable performance not only across age groups but between first and second halves of the season. Participants in the U10s-U12s category experienced decrements in sprint speed, COD ability and lower body power as measured by CMJ, despite noted increases in strength, whereas the U14s-U16s experienced improvements in speed and COD only. In terms of practical applications to training, a goldilocks effect may apply. Where hugely variable athletes may benefit from better load distribution, but less opportunity for adaptation, and less variable athletes capitalise on adaptation developments but become more exposed to repeated focused loads (Murray, 2017). All age groups aerobic capacity improved postseason, however, improvements appeared to be limited to the second half of the season, with notable reductions evidenced in pre to mid-season measure. This additional mid-season measure suggests that additional test sessions to pre and post-season provide more information on regression and development of performance variables throughout a season, and should be a methodological consideration in future research design.

Volleyball athletes aged U19 showed a significant increase in jump performance variables and isometric knee extension over a shorter 4-month period between preparatory pre-season and the competitive aspect of their season (Rousanoglou, Barzouka and Boudolos, 2013). Whilst most seasonal variation data appears to be drawn from two measures of pre and post-season data, increased data collection points of a multi-longitudinal approach may be more insightful to practitioners. Whilst most of the data available appears to be limited to football. It appears that when considering longitudinal monitoring of performance variables through a season the consideration of the context of growth and maturation and its potential impact on physical performance is an important factor (Emmonds *et al.*, 2020).

In addition to mid-season or extra data collection time points, studies investigating the seasonal variation of performance variables must account for the idiosyncrasies of growth and maturational stages (Monasterio *et al.*, 2020). Although these studies demonstrate seasonal variation into physiological variables, literature in the field relating specifically to measures that monitor NMC specifically are limited. To date, only one study analysing lower limb NMC changes over the course of a football season found that youth male players had a decrease in NMC through that competitive season as evidenced by peak landing forces during hopping tasks (Lloyd *et al.*, 2020).

Literature that examines seasonal variation in NMC via qualitative measures remains even more sparse, with only one paper (Sprague, Mokha and Gatens, 2014) documenting changes in Functional Movement Screen (FMS) component scores for deep squat, inline lunge, SLR and rotary stability over a 3-month period. Participants were also of college-age and therefore it appears thus far no paper has considered a seasonal variation of qualitative NMC measures and potential influence of maturity status.

Whilst the interconnection, if any, between growth and maturation and adolescent injury risk is still emerging within the literature, changes in NMC appear to be related to changes in athletic performance as well as growth-related injuries (Sprague, Mokha and Gatens, 2014; Brenner *et al.*, 2016; Emmonds *et al.*, 2020; Estevan *et al.*, 2020; Monasterio *et al.*, 2020). Due to limited longitudinal research into the seasonal variation of performance measures in youth and adolescent athletes collectively, and the specific shortage of research around qualitative performance measures of NMC, additional research would be advantageous for practitioners working with this population to establish any through seasonal or yearly differences noted across adolescent athletes. Further informing how growth and maturation may impact on the performance of unilateral tasks by providing additional contextual information comparative to a single reductionist biomechanical measure.

Positive involvement in sport throughout an academic year or competitive sporting season depends upon identification, monitoring, expansion and maintenance of multiple caveats of physical performance, especially that involving movement quality and NMC (Sprague, Mokha and Gatens, 2014; Monasterio *et al.*, 2020). The establishment of both the short- and long-term stability of performance measures is frequently overlooked (Bidaurrazaga-Letona *et al.*, 2015), but imperative if normative seasonal variation in movement quality and NMC in the adolescent population is to be understood.

Reliability of the QASLS tool was established in chapter three, and further advanced in the youth population in chapter four. These results have provided cross-sectional data examining QASLS scores during the performance of two unliteral tasks in multisport athletes across maturational groups. Whilst the cross-sectional data has contributed to the research base of one-off evaluation and within and between athlete monitoring of different maturational categories, it is limited in its ability to provide insight and inform practitioners around longer-term movement quality performance changes or development.

Longitudinal analysis better informs practitioners around the development of physical qualities such as NMC or movement quality, as well as insight to the interrelational impact of the competition and training environment on the evolution of these qualities (Morris *et al.*, 2018). The use of multiple observations of the same participants over a longitudinal time-frame approves better identification of any performance differences observed between and within adolescent participants (Saward *et al.*, 2016). Given the huge variation that is generally seen in human movement and has indeed been observed during the duration of this study, as well as performance impacting growth and maturational factors that can potentially occur during a competitive or academic season, the establishment of the longitudinal performance measure of the QASLS tool in a youth adolescent population is important. Therefore, additional research is required with participants involved with different sporting backgrounds to understand if this is a viable method for collecting movement quality data that can mitigate for maturational shifts. Additionally, assisting practitioner understanding of the holistic movement quality development of adolescent youth multisport athletes.

Collectively the literature pertaining to seasonal or yearly variation in movement quality during qualitative assessment in the adolescent youth athletes is scarce. With the ever-increasing demands on youth athletes to develop, identify and perform at younger and younger ages (Jespersen *et al.*, 2014; Morris *et al.*, 2018; Emmonds *et al.*, 2020) additional investigation remains necessary. This could further inform practitioners around potentially expected seasonal variation in an adolescent cohort and how this may affect movement quality underpinned by NMC performance, and subsequent impact on injury risk.

As such the purpose of this study was to utilise a longitudinal approach to examine seasonal variation and changes in the performance of two unilateral tasks as assessed by QASLS tools during an academic school year that encompassed several sports seasons. It was hypothesised that QASLS scores would change significantly throughout the course of a season for both unilateral tasks. A secondary aim was to further explore the interactions between sex-specific differences and compound QASLS scores of multisport athletes in different PHV groups, to establish the main effects of gender on task performance. The final aim of the study was to understand the interaction between task performance and maturational status, it was also hypothesised that changes would be classifiable according to maturity band status, and that distinct trends of QASLS component strategies would be identifiable in relation to the predicted percentage of adult height (PAH%). It is anticipated this study will contribute to practitioner understanding of how the QASLS profiling tool maybe applied over a season in adolescent athletes in different maturational phases to further strengthen the application of profiling. Using PAH% to identify specific strategies of movement that have been identified as potential injury risk factors also seems a logical approach to further understand the interactions of movement quality and injury risk within this population.

5.2 Methodology

Summary of Study Aims

The aims of the study were to demonstrate if performances of two unilateral loading tasks by youth adolescent athletes changed over the course of a season, to identify any interactions between sex-specific performance differences, and to identify if maturational status impacts on task performance. It is expected this study will contribute to the third objective of this thesis by establishing if longitudinal movement pattern variation occurs within an adolescent cohort

5.2.1 Participants

The cohort for this study was selected from several sporting clubs and academies from across England. Initially a number of clubs, groups and societies expressed interest in the study and identified suitable participants only to withdraw involvement in the study. This has been discussed prior in the preface, but the inclusion and exclusions of participants are displayed in figure 5.1. Seventy youth athletes from a Dance School, Rugby Academy, Private School, Athlete Academy within that public school and Tennis academy participated in all 3 phases of this study. Descriptive statistics are in table 5.1. Participants all identified 1 sport as their "main" sport, were involved in 1 or 2 additional sports(s) that involved the attendance at one organised training session or competition-based session per week. All participants were

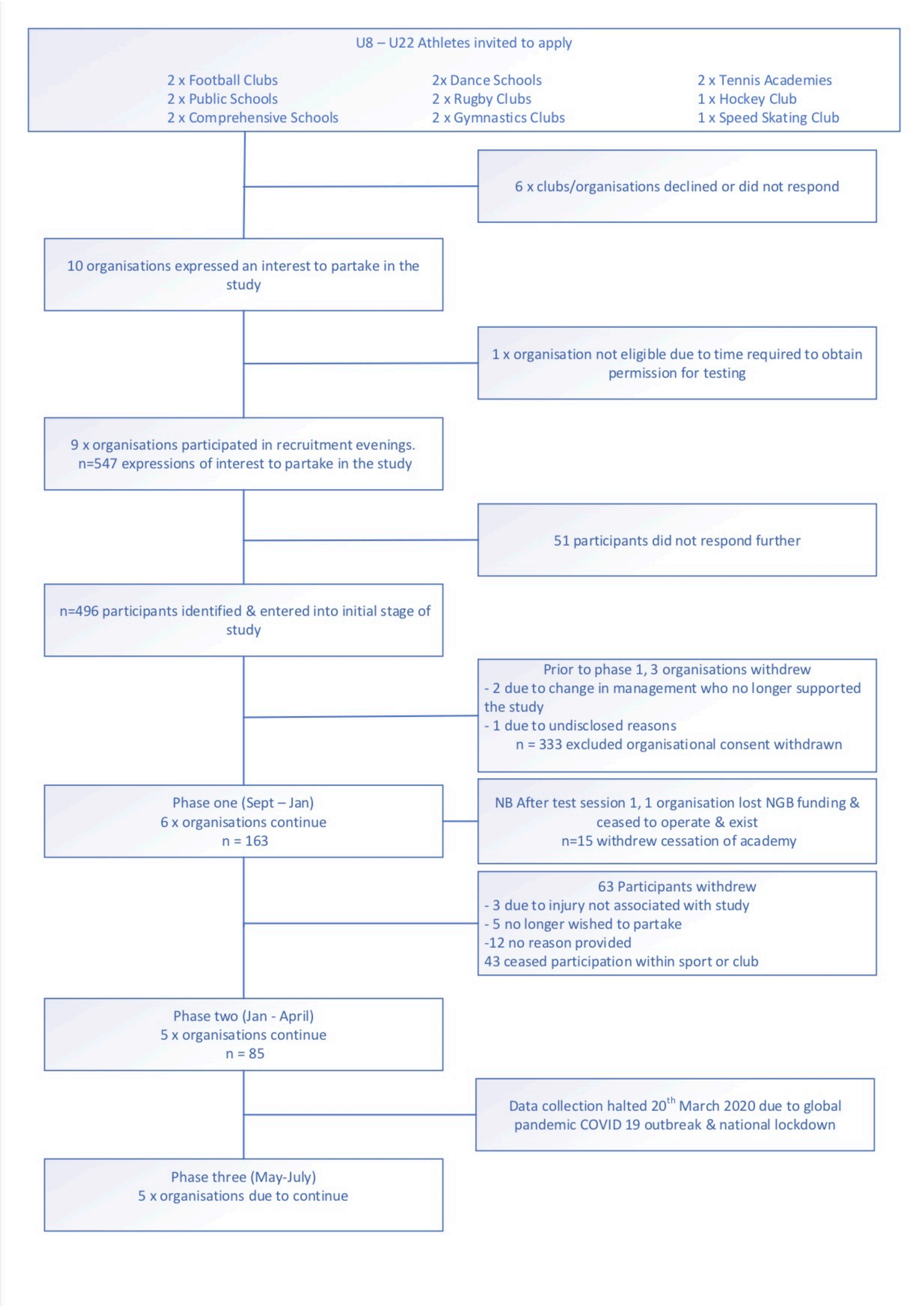


Figure 5.1 – Flowchart of participants in qualitative analysis of SLS and SLL across all test phases

Table 5.1 Anthropometric & maturity characteristic (mean ±SD) by sporting organisation at phase 1

	Whole Group (n=70)	Dance School (F=18,M=13)	Rugby (F=3,M=5)	Private School/Athlete Academy (F=12,M=12)	Tennis Academy (F=4,M3)
Chronological Age (years)	14.2 ± 3.3	16.9 ± 2.7	10.8 ± 3.2	12.2 ± 1.8	14.5 ± 1.0
PHV off-set (years)	0.4 ± 2.8	2.8 ± 1.8	-2.5 ± 2.9	-0.7 ± 1.9	1.2 ± 1.6
Predicted percentage of adult height (PAH%)	91.7% ± 14.21	98.7% ± 5.4	80.8% ± 15.7	89.3% ± 8.41	94.5% ± 4.35
Mass Kg	50.9 ± 13.2	53.9 ± 10.7	55.0 ± 21.3	35.6 ± 11.3	59.8 ± 8.0
Height cm	158.4 ± 13.6	163.7 ± 11.0	156.0 ± 17.4	147.7 35.6 ± 12.7	166.8 ± 4.7
Growth Spurt Status Male	Pre=8,Circa=13,Post=12	Pre=0,Circa=4,Post=9	Pre=4, Circa=0, Post=1	Pre=4, Circa=7, Post=1	Pre=0, Circa=2, Post=1
Female	Pre=1,Circa=15,Post=21	Pre=1,Circa=3,Post=14	Pre=0, Circa=2, Post=1	Pre=0, Circa=10, Post=2	Pre=0, Circa=0, Post=4

cm= centimetres=female, Kg= kilograms, M=Male, PHV= peak height velocity, SD= Standard deviation,

Table 5.2 Growth spurt status by sex

gender/phase of growth spurt	Pre-PHV	Circa-PHV	Post-PHV	Total
Male	8	13	12	33
Female	1	15	21	37
Total	9	28	33	70

required to be injury-free during testing, with participant assent and parental consent along with physical readiness questionnaires were completed before phase one training. The University of Salford research and ethics committee approved the study following the declaration of Helsinki (1983).

5.2.2 Research Design

Seasonal variation of the performance of two unilateral tasks as evaluated by QASLS score was analysed using a repeated measures design. Each participant was tested in their own training facility environment through the school year/sporting season. Phase 1 (P1) testing occurred in September/October at the start of the school year, Phase 2 (P2) testing occurred 16 weeks later in the midpoint of the school year in January and Phase 3 (P3) testing was due 16 weeks after in May/June at the end of the academic year and most sporting seasons. All measurements were recorded within a 16-day period. Testing, both anthropometric and movement quality, was conducted by the same researcher (GP) on all occasions. Participants were encouraged to wear the same or similar training kit none of the participants wore shoes and all were encouraged to continue with their normal daily routines regarding nutritional and fluid intake. Although testing was completed on different days for different organisations, each organisations testing occurred on the same day at the same time in their own test venue. Task instruction was standardised (see 4.2.3), task order was randomised and 5 repetitions of both tasks from each session were used for data analysis.

5.2.3 Procedures

Test space was configured via the methods described in chapter three and four. Anthropometric data was collected via the two none invasive methods of maturity offset and predicted percentage of adult height (PAH%), with compound and component movement strategies classified in maturity bands pre-PHV (<85%), circa-PHV (85-96%) and post-PHV >96% (Parr *et al.*, 2020) (please refer to 4.2.3). Movement assessment tasks of single-leg squat and single-leg land were also conducted as via the methods described in section 4.2.3 but without the anatomical landmark marking.

5.2.4 Impacts of COVID 19

On the 23rd March 2020, the United Kingdom entered a nationwide lockdown that declared the closing of non-essential businesses and services, and the immediate ceasing of unnecessary social contact. The impacts of this have been far-reaching into every aspect of livelihood, with society witnessing the unprecedented blanket closure of schools and sports facilitates. Whilst phase 1 and phase 2 data collection went unimpeded, in line with social distancing measures set out by the central government and national governing sporting bodies phase 3 data collection was unable to take place as planned. The week before lockdown all organisations agreed to an earlier data collection for phase 3. Some participants were unable to partake due to the short notice and other logistics, meaning less participants were captured 9 weeks earlier than originally scheduled. Whilst this obviously means that data analysis must be interpreted with some caution, it is hoped that the additional phase 3 data set will provide sufficient information for proof of concept around the seasonal variation within a sporting season or academic year.

5.2.5 Statistical Analysis

Compound QASLS Score – longitudinal performance

A general linear model was conducted using SPSS (Version 25, SPSS Inc., Chicago, IL) statistical software. Two-way mixed-effects analysis of variances (ANOVA) was selected to determine if compound QASLS scores of the right and left limb, of two unilateral tasks changed between youth athletes from different PHV groups during three different times phases of a sporting season/academic year. Performance variable change was evaluated along with the covariance influence at each phase of data collection. The ANOVAs dependent variables were change in raw QASLS compound score and absolute difference in score. The between subject's independent variable included PHV group (i.e. pre, circa or post), the within subject's variable included phase time of test (i.e.: phase 1 - pre (P1), phase 2 – mid (P2), phase 3 - end (P3). Any change in maturity was used over the phase of the study (e.g. P1 to P2) was considered as the covariate. F test was selected to determine the significance of the independent variables, with Bonferroni correction applied to control for associated type one error of multiple comparisons, and an alpha level of.05 applied. Variances were homogeneous ($p>.05$)

and covariances (p >.001) as assessed by Levenes test and M boxes tests respectively, during phases one and two for both limbs and tasks, these assumptions were violated for phase 3 during the single-leg squat tasks. Mauchly's test of sphericity was utilised to establish the assumption of sphericity to the two-way interactions, and where violated the greenhouse geiser test was used for interpretation.

Normal distribution of data was assessed via Shapiro Wilks test (p>.05), which yielded mixed results. For the single-leg squat task, the post-PHV group was non-normally distributed on all phase testing occasions, and for the SLL tasks, the pre-PHV Group during phase 2 and the post-PHV groups across all test occasions were also nonnormally distributed. Whilst non-normal distribution of data arises frequently in the sports sciences, despite the considered robustness of the ANOVA to deviations of normality, currently, there are no non-parametric alternatives for mixed analysis of variances (Oliver-Rodríguez and Wang, 2015)). Due to this, the Friedman test was run in addition to consider that impact of time in season on compound QASLS scores and absolute differences.

Compound QASLS Score – Sex-specific performance differences

Following normality testing, corresponding differences between female and male multisport athletes and QASLS compound scores were analysed by the non-parametric Mann Whitney U, with two-way analysis of variance (ANOVA) chosen to analyse differences in compound QASLS scores between females and males in different PHV-groups. Due to only 1 female athlete classifying as prepubertal (Table 5.2) only athletes from the circa and post-PHV groups were analysed to establish sex-specific differences and maturational status, as no meaningful analysis could be performed on the pre-PHV group.

Component QASLS Score

Each component of the QASLS score was compared by frequency of use to a percentage of predicted adult height (PAH%), with QASLS strategies classified according to bio-banding principals of maturity status. Statistical analysis was calculated via custom-made spreadsheet (Microsoft Excel Version 16.16.22) and analysed via Tableau (version 2019.1).

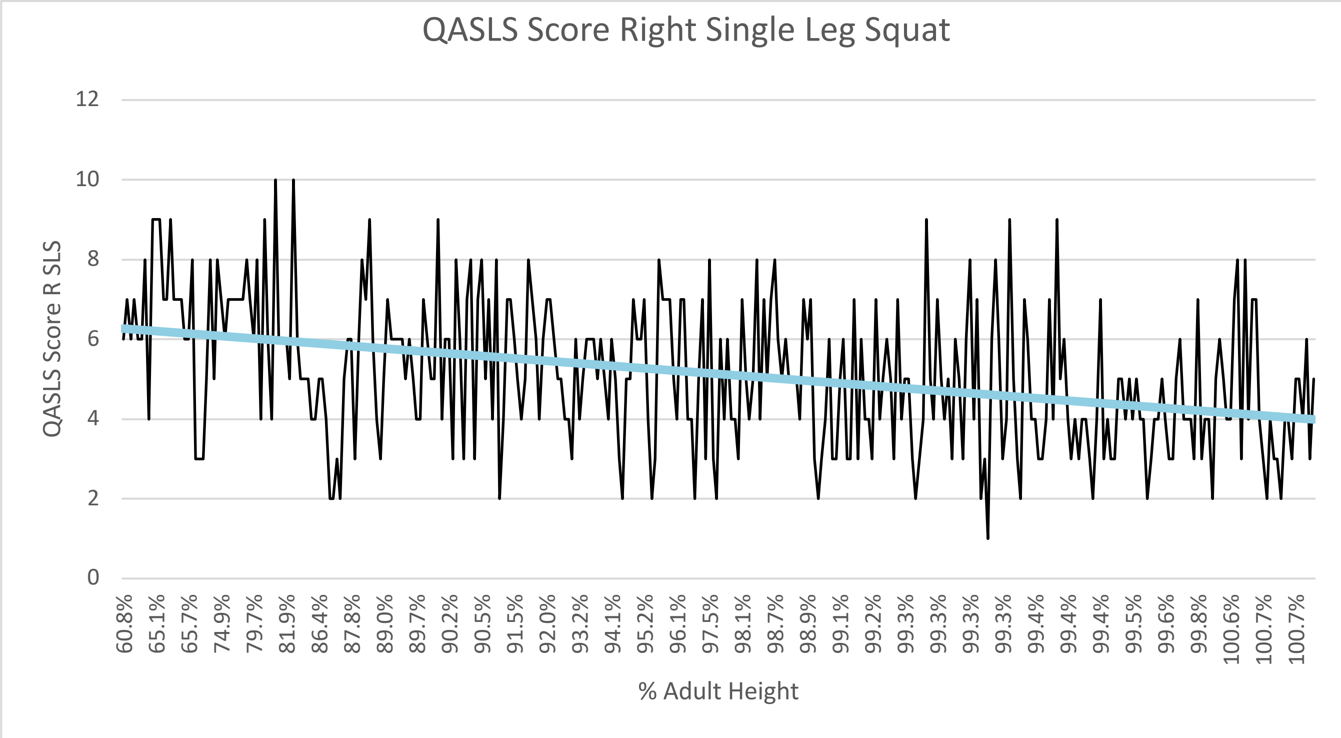
5.3 Results

Raw compound QASLS Schools and absolute difference scores for all participants and for each organisational group are presented in table 5.2. Figures 5.2 and 5.3 show the mean compound QASLS score relative to the predicted percentage of adult height (PAH%) for the SLS and SLL respectively. Compound QASLS scores for SLS did not change over the course of a season or academic year but did for the SLL task for the Circa and Post PHV groups. There where between PHV group differences of task performance for both the squat and landing, with Post-PHV group utilising fewer component strategies than the Pre-PHV group. No interactions between sex and compound QASLS scores for either limb or task were observed.

Table 5.3 Mean (±SD) Descriptive statistics for raw compound QASLS score and absolute difference in scores by unilateral tasks in each organisation at P1, P2 and P3

Task & Limb	Whole Group (n=70)			Dance School (F=18, M=13)			Rugby Academy (F=3, M=5)			Private School/Athlete Academy (F=12, M=12)			Tennis Academy (F=4,M=3)		
	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3
SLS R	5 (2.1)	5 (1.7)	6 (2.6)	4 (1.9)	4 (1.4)	5 (1.8)	7 (1.6)	7 (1.6)	6 (1.6)	6 (1.9)	6 (1.6)	6 (1.2)	5 (2.3)	5 (1.7)	7 (1.5)
SLS L	5 (2.1)	5 (1.8)	6 (2.7)	4 (1.5)	4 (1.7)	5 (1.7)	7 (1.1)	7 (1.5)	7 (0.5)	6 (2.1)	6 (1.6)	6 (1.5)	6 (2.0)	6 (1.4)	7 (1.9)
SLL R	5 (2.1)	5 (1.6)	5 (1.3)	5 (1.8)	4 (1.4)	5 (1.1)	6 (1.1)	6 (1.5)	7 (0.8)	5 (1.4)	6 (1.5)	5 (1.3)	6 (1.6)	5 (1.3)	5 (1.3)
SLL L	5 (2.1)	5 (1.5)	5 (2.2)	4 (1.3)	4 (1.6)	5 (1.1)	6 (1.6)	5 (1.5)	6 (2.2)	5 (1.5)	5 (1.2)	5 (1.3)	4 (1.6)	6 (1.5)	5 (1.5)
Absolute difference (ABS) in score															
SLS R	1 (1.3)	1 (1.2)	1 (1.3)	1 (1.3)	1 (1.3)	2 (1.4)	1 (1.5)	2 (1.5)	2 (2.0)	1 (1.2)	1 (1.1)	1 (1.0)	2 (1.7)	2 (1.6)	2 (1.0)
SLS L	1 (1.1)	1 (1.1)	2 (1.3)	1 (1.1)	1 (1.0)	1 (1.3)	1 (0.8)	1 (1.0)	1 (0.9)	1 (1.2)	1 (1.2)	2 (1.4)	1 (0.5)	1 (0.9)	1 (1.1)
SLL R	1 (1.0)	1 (1.1)	1 (1.0)	1 (0.9)	1 (0.8)	1 (1.1)	1 (0.9)	2 (1.6)	1 (0.8)	1 (1.2)	1 (1.1)	1 (0.8)	1 (1.1)	1 (1.3)	1 (1.3)
SLL L	1 (0.8)	1 (1.1)	1 (1.0)	1 (0.7)	1 (0.6)	1 (0.7)	2 (1.8)	2 (2.3)	2 (1.8)	1 (0.9)	1 (0.7)	1 (1.1)	1 (1.1)	2 (1.6)	1 (1.0)

ABS = Absolute difference, Diff = difference, P = Phase, QASLS = Qualitative assessment of single leg loading, SD = standard deviation



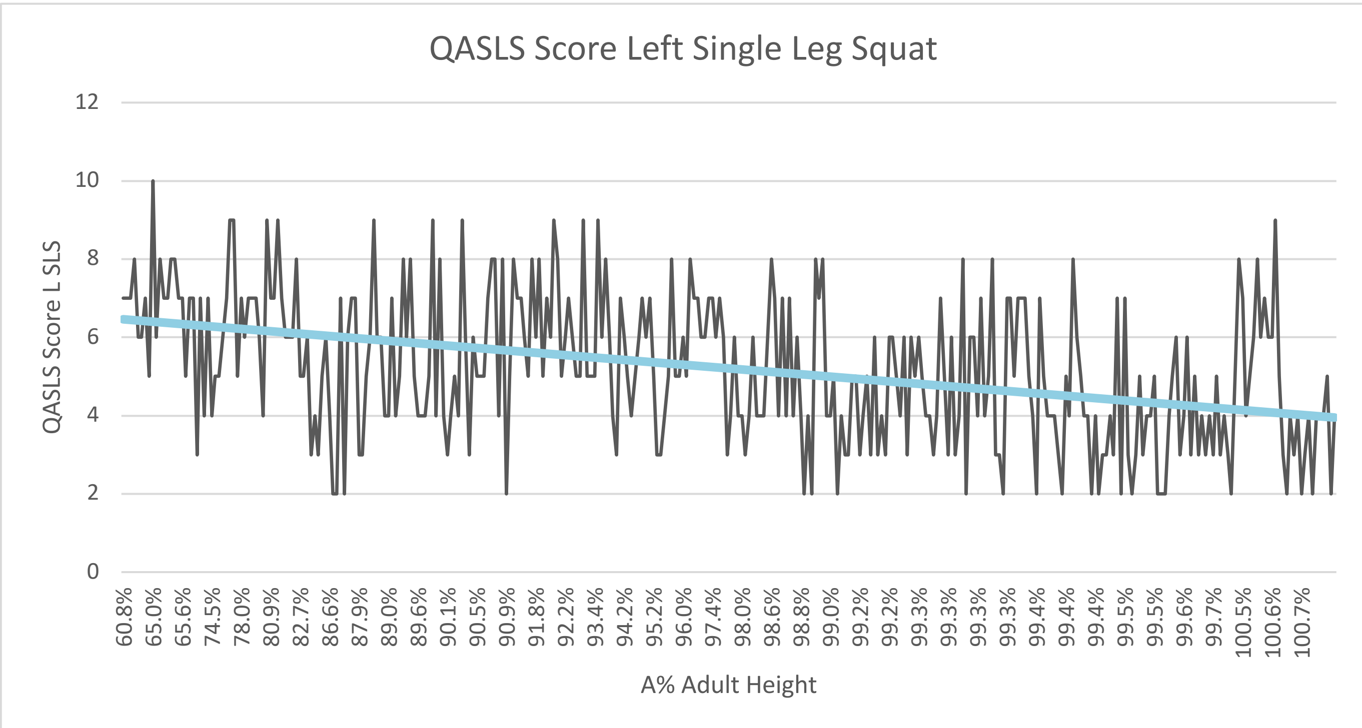
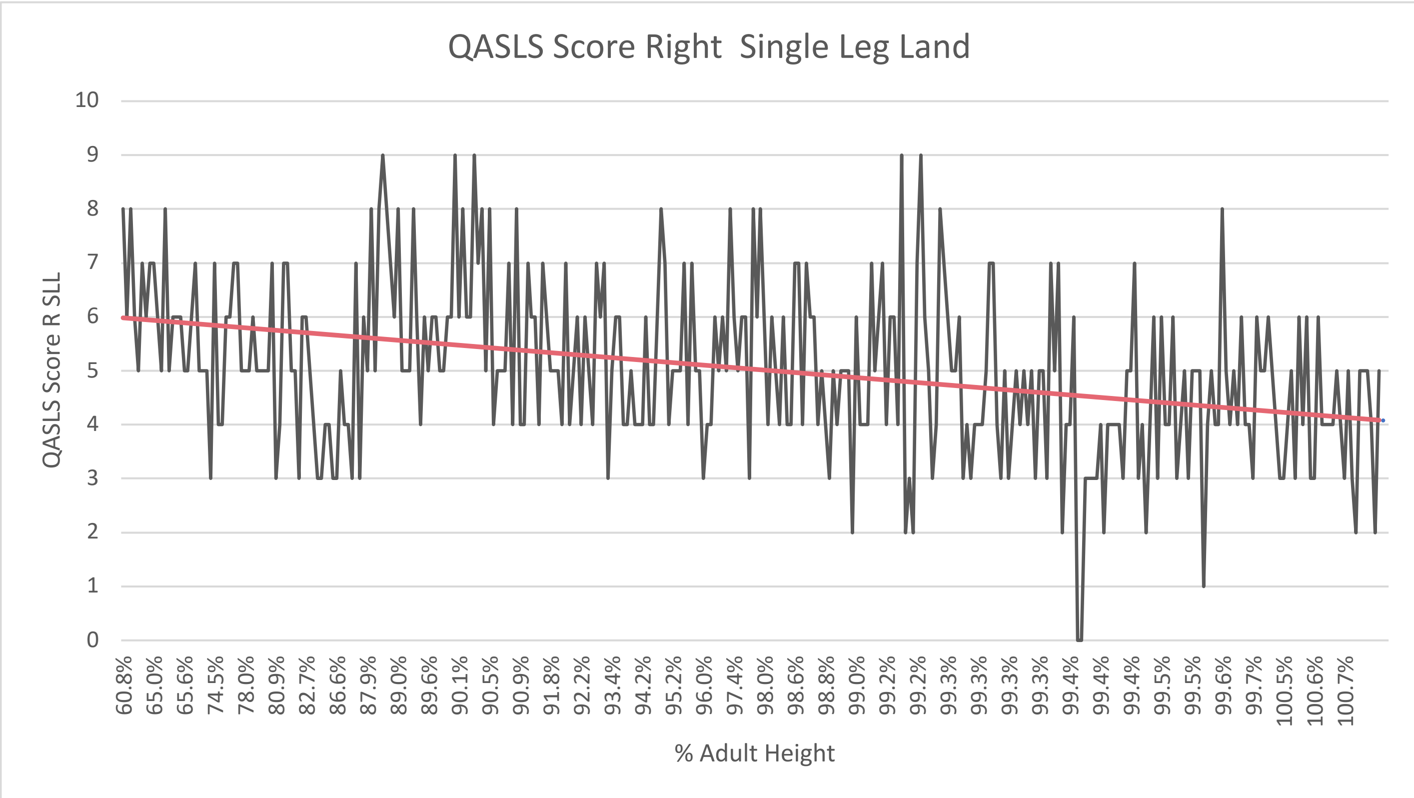


Figure 5.2 mean compound QASLS score relative to predicted percentage of adult height (PAH%) for single leg squat task



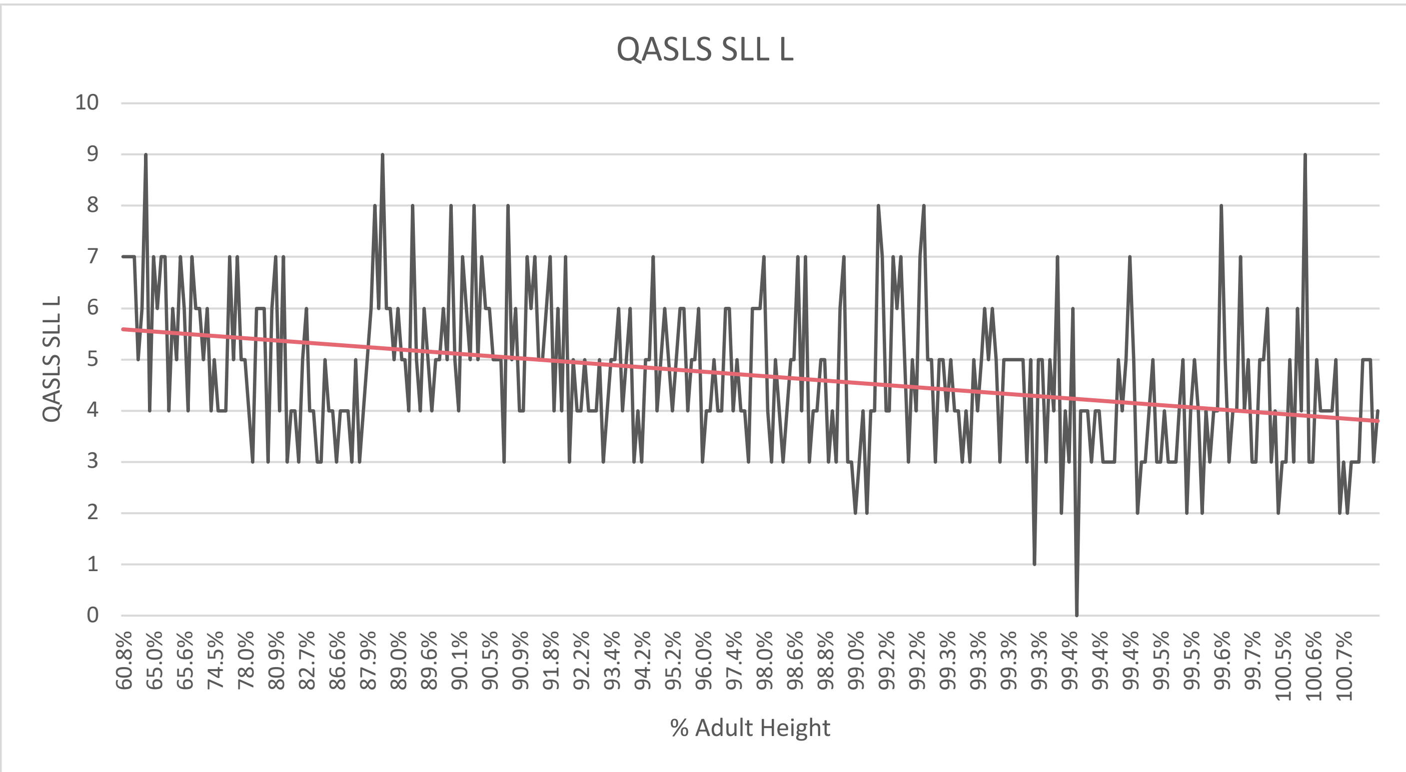


Figure 5.3 mean compound QASLS score relative to predicted percentage of adult height (PAH%) for single leg land task

Compound QASLS Score – Sex-specific performance differences

Mann-Whitney U test was run to determine if there were differences in compound QASLS scores between females and males across the whole participant group, distribution of the compound scores for males and females were similar as assessed by visual inspection, medial scores for female and males were not significantly difference across either limb or task (Table: insert the Mann Whitney U one). Two-way ANOVAS were conducted to examine the effects of gender and maturational status (PHV groups) on compound QASLS scores of the right and left limbs during the unilateral tasks of landing and squatting. Residual analysis was performed to test for assumptions of the two-way ANOVA. The interaction effect between sex and compound QASLS score was not significantly different for either limb or task (Right SLS = F(1,55)=.927, p=.340, partial η^2 =.017; Left SLS = F(1,55)=2.794, p=.100, partial η^2=.048; Right SLL= F(1,55)=.674, p=.415, partial η^2=.012; Left SLL = F(1,55)=.014, p=.905, partial η^2=.003). Therefore, analysis of the main effect of sex on compound QASLS scores was also performed, all pair-wise comparisons were Bonferroni adjusted, which also indicated the main effects of sex was significantly none-significant across circa-PHV (Right SLS = F(1,55)=1.791, p=.186, partial η^2 =.001; Left SLS = F(1,55)=3.465, p=.068, partial η^2=.059; Right SLL= F(1,55)=1.398, p=.242, partial η^2=.025; Left SLL = F(1,55)=.037, p=.848, partial η^2=.001), or post-PHV groups (Right SLS = F(1,55)=.066, p=.941, partial η^2 =.001; Left SLS = F(1,55)=.162, p=.608, partial η^2=.003; Right SLL= F(1,55)=.012, p=.912, partial η^2=.000; Left SLL = F(1,55)=.165, p=.686, partial η^2=.003).

Compound QASLS Score Single Leg Squat (SLS) Task

There were no statistically significant interactions between the PHV group and phase of testing on QASLS compound score for either the right (F(4,130)=2.231,p=.060) or left limb (F(3.627,117.9)=1.230, p =.302). Right SLS compound QASLS score did not significantly change through the season (F(2,130) =.668,=p.514) but was statistically different for the left limb during the different testing occasions (F(1.813)=117.9,p=.043). Post hoc pairwise analysis revealed that left SLS compound score significantly changed between phase 2 and phase 3 (.562(95%CI, .035-1.089),p=.033) but not from P1 to P2 or P1 to P3. The main effect of maturational group showed significant differences in compound QASLS score between PHV groups for both the right (F(2,65)=5.095,p=.009) and left limbs (F(2,65)=5.478,p=.006). Post hoc analysis yielded significant differences between pre and post-PHV group for right SLS (1.278(95%CI,.170-2.386,p=.018), and between pre and post groups (1.343(95%CI,.130-2.555),p=.025) and circa and post group differences (1.132(95%CI, .070-1.834),p=.033) for the left limb.

Table 5.4 Mean Compound QASLS Scores across PHV Groups

PHV-Group	Right Limb			P	Left Limb			P	Post Hoc Differences
	P1	P2	P3		P1	P2	P3		
Single Leg Squat									
Pre	6.1	6.2	5.7	.488	6.6	6.2	5.7	.232	N/A
Circa	5.5	5.4	5.8	.109	6	5.7	6	.280	N/A
Post	4.2	4.8	5.2	.018	4.5	4.5	5.1	.003	P1 & P3, P2 & P3
Single Leg Land									
Pre	5.8	5.3	5.1	.139	5.4	5.1	4.8	.779	N/A
Circa	5.4	6.2	5.0	.002	5.7	5.2	4.7	.006	P2 & P3, P1 & P3
Post	4.6	4.2	5.1	.015	4.1	4.3	4.5	.033	P2 & P3, P1 & P3

N/A = Not applicable, = P-value, PHV = peak height velocity, P1= Phase 1, P2= Phase 2, P3 = Phase3, QASLS= qualitative assessment of single leg loading.
P = <.005, Significance determined with Friedman Test

Due to the non-normal distribution of data the Friedman test was run to determine if there were differences in PHV group compound QASLS scores during the testing period and results are presented in Table 5.3. There were observable differences in pre and circa – PHV groups, but these differences were statistically not significant. Compound QASLS scores were significantly different during the season for the post-PHV group for both the right (X2(2)=8.052,p=.018) and left limb (X2(2)=11.352,p=.003) between P1 and P3.

Compound QASLS Score Single-Leg Land (SLL) Task

Contrary to SLS performance, there were statistically significant interactions between the PHV group and phase of testing in QASLS compound scores for both the right (F(4,130)=8.288=p<.0005) and the left (F(4,130)=4.277,p=.003) limbs during SLL. Statistically significant differences in R SLL compound QASLS scores were observed between two PHV groups during P1 (F(2,80)=4.187,p=.019) and P2 (F(2,80)=14.940,p<.0005). At P1 there were significant differences between the pre and post PHV groups (1.21 ± SE 0.45,p=0.23) and at

P2 between pre and post (1.08 ± SE .40, p=.020) and circa and post (1.9 ±SE.36, p<.0005). No significant differences were evident between the pre and circa groups during any of the phases of testing (P1=.43 ± SE.50, p=.650; P2 =.83± SE.43, p=.139; P3=.15 ±SE.46,p=.941). The main effect of testing phase showed a statistically significant difference for the circa-PHV group (F(2,36)=9.069,p=.001) and post PHV group (F(2,70)=4.696,p=.012), but not for the pre-PHV group (F(2,24)=3.059,p=.066). For both the circa (Mean=1.474 ±SE.30, P<.0005) and post PHV (mean=.778± SE.22,p=.0005) groups there was a significant decrease in compound score between P2 and P3, however, these differences were not significant between P1 or P2 or P1 and P3 (P>.05).

Like the single-leg squat, due to the non-normal distribution of data Friedman's test was run to determine if there were differences in compound QASLS scores of the PHV groups during the testing period and are presented in Table 5.3. There were observable differences in pre-PHV group compound QASLS score but these differences were statistically not significant. For the circa-PHV group compound, QASLS scores for the right limb were significantly different during the season between phases 1 to 2 (p=.004) and 2 to 3 (p=.042) and between phases 1 to 3 (p=.006) for the left limb. For the post-PHV group, statistical differences were present for both the right (p=.010) and left limb (p=.022) between phase 1 and phase 3.

Component Scores

The pre-PHV group used large percentages of all QASLS components strategies comparative to other PHV groups. This is also reflective of the larger compound QASLS scores observed within this group. The hip adduction strategy was the least selected strategy across all PHV groups and tasks (2–12%), with loss of horizontal pelvic plane occurring the most (75–92%). Figure 5.4 shows the frequency of component strategy selection by predicted PAH% between the limb and unilateral task.

There was an observable difference in some strategies between growth groups and unilateral tasks (tables 5.5 and 5.6). Each QASLS component strategy selection by limb and task is presented in figure 5.5. Use of an arm strategy was used 60–70% of the time by the pre-PHV group during both unilateral tasks. This increased slightly invest circa–PHV group during squatting (72–76%) but reduced during landing (48–52%). This decrease in use continued into the post-PHV group in both tasks. The use of the trunk occurred similarly in all growth groups during landing (60–75%) with the post–PHV group selecting it less during squatting (44–57%) than either the pre or circa groups (60–81%). Loss of horizontal pelvic pain was also very similar across all groups and both tasks with slightly higher use during squatting (80–92%) comparative to landing (75–92%), and within the circa and post –PHV groups (84–92%).

The pre-PHV Group used more pelvic tilt strategies than any other group during both tasks (27–52%) with the use of this strategy appearing to diminish through growth, with 11–15% use during landing and 9–11% during squatting in the post-PHV group. Increased movement of the NWB thigh occurred in all groups frequently during landing (72–94%) and squatting, although it was more prominent strategy in the pre-PHV Group (88–96%) relative to the circa (72–80%) and post-PHV (57–60%) group. There were observable increases in knee strategies in the circa-PHV Group during squatting with noticeable valgus occurring in 92–96%, and significant valgus noted at 40%.

During landing significant valgus reduced to 2–6% in the post–PHV group. Ankle strategies were most frequent in the pre-PHV Group 78% using a touchdown of the NWB leg during squatting and 25 to 27% during landing. Wobbling of the stance leg was also higher in this group with similar values seen (28–37%) across both tasks. The utilisation of ankle strategies also appears to reduce through growth with 12–28% of the circa–PHV Group and 22–31% requiring a touchdown during squatting. This reduced again during landing with only 2 to 4% of post-PHV participants using a touchdown for displaying noticeable wobble of the stance leg.

Table 5.5 Percentage of athletes utilising QASLS component use by PHV group during Single Leg Squat

	Pre-PHV		Circa-PHV		Post-PHV	
	Right Limb	Left Limb	Right Limb	Left Limb	Right Limb	Left Limb
Arm Strategy	60%	70%	72%	76%	35%	51%
Trunk Alignment	71%	81%	60%	60%	44%	57%
Pelvic Plane -Horizontal	85%	80%	92%	88%	91%	91%
Pelvic Plane – Tilt or Rotations	52%	49%	24%	72%	9%	11%
Thigh -NWB hip adduction	12%	4%	3%	2%	4%	8%
Thigh – NWB not in neutral	88%	96%	72%	80%	60%	57%
Knee – noticeable valgus	77%	62%	96%	92%	53%	64%
Knee – significant valgus	25%	20%	40%	40%	13%	11%
Touch Down NWB	78%	78%	28%	12%	22%	31%
Stance leg wobbles	28%	37%	16%	24%	8%	8%

Table 5.6 Percentage of athletes utilising QASLS component use by PHV group during Single Leg Land

	Pre-PHV		Circa-PHV		Post-PHV	
	Right Limb	Left Limb	Right Limb	Left Limb	Right Limb	Left Limb
Arm Strategy	67%	64%	48%	52%	24%	47%
Trunk Alignment	71%	75%	64%	64%	60%	68%
Pelvic Plane -Horizontal	75%	81%	84%	92%	88%	84%
Pelvic Plane – Tilt or Rotations	31%	27%	20%	12%	11%	15%
Thigh -NWB hip adduction	2%	1%	13%	4%	8%	0%
Thigh – NWB not in neutral	94%	91%	72%	84%	84%	88%
Knee – noticeable valgus	62%	45%	68%	48%	42%	4%
Knee – significant valgus	24%	7%	28%	12%	6%	2%
Touch Down NWB	25%	27%	8%	12%	4%	2%
Stance leg wobbles	31%	37%	8%	28%	4%	2%

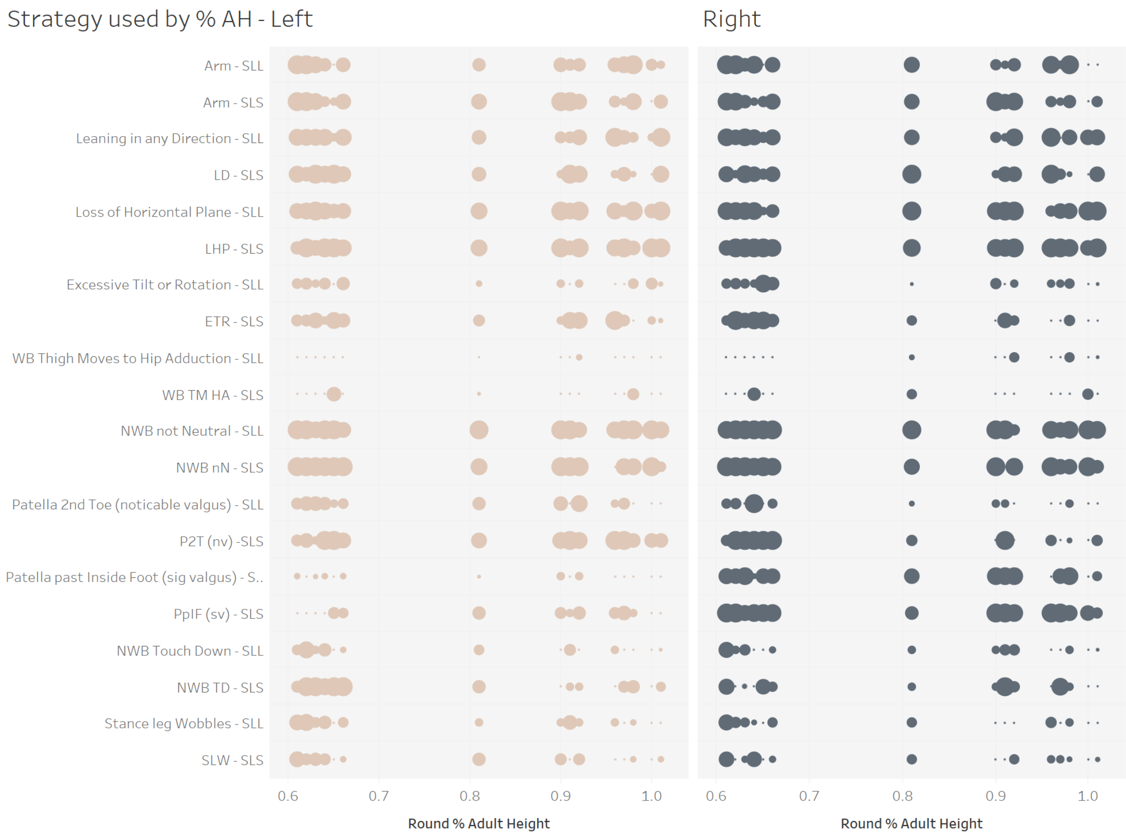


Figure 5.4 Frequency of QASLS component strategy selection by limb in participants as classified via PAH (%)

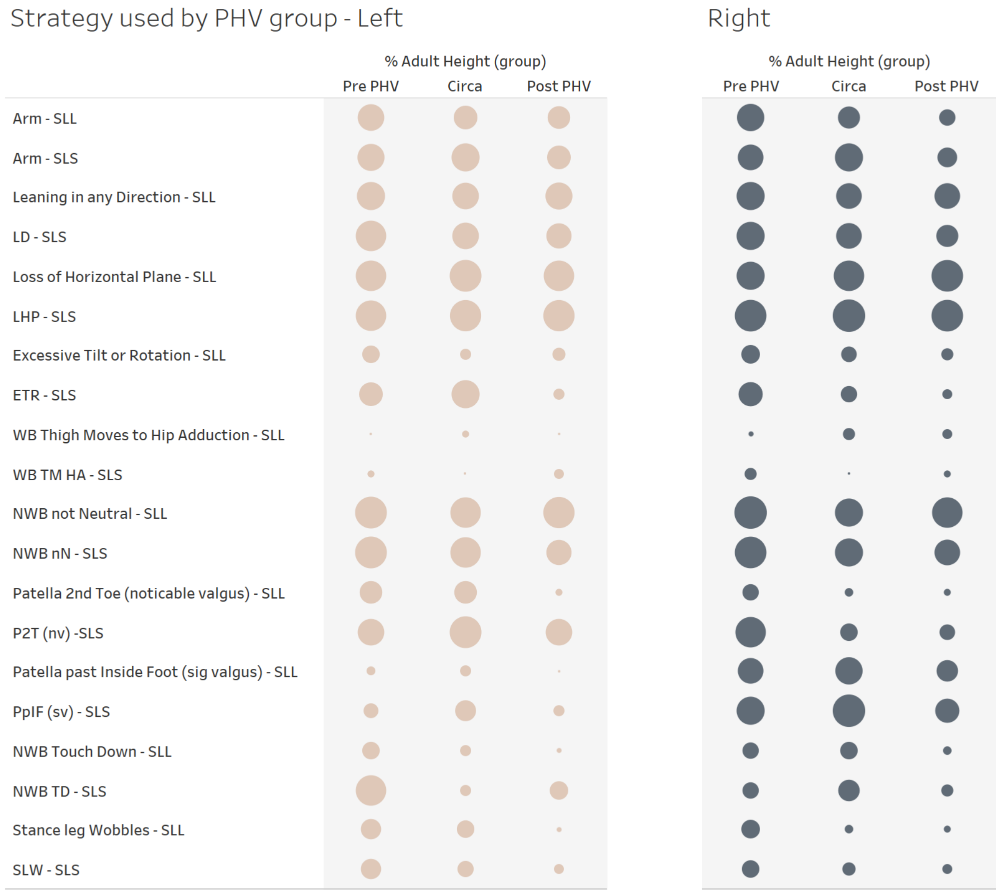


Figure 5.5 QASLS component strategy selection by limb as selected by phase of PHV

5.4 Discussion

The purpose of this study was to investigate seasonal variation in the two unilateral loading tasks squatting and landing across a year in adolescent athletes, using the QASLS tool. Consideration was also given to maturity status, and the interaction of sex-specific differences in QASLS compound scores. To provide additional deep insight into the relationship between unilateral task performance and phase of growth, compound and, component QASLS score was longitudinally analysed from the start of the academic year/ Sporting season, the midpoint in January, and the end of the year/Sporting season (although this occurred early due to Covid-19). When evaluated by compound QASLS score, results demonstrated that during the year there was no significant change in single-leg squat performance, regardless of the phase of growth. Whereas, single-leg land performance did change between the start and mid, and mid to end phases for the circa-PHV groups, and between the start and end phase of testing in the post-PHV group. Overall a trend in the reduction of compound QASLS scores through growth in both tasks was observed, with pre-PHV athletes demonstrating higher mean compound scores and post-PHV athletes (figures 5.2 and 5.3). No specific sex-specific differences in compound QASLS scores were observed in either limb or unilateral task in circa and post-PHV multisport athletes.

Whilst overall compound QASLS score did not change significantly during squatting, or landing in the pre—PHV group, component QASLS strategies did. Suggesting that the composition of the compound score, and thus the performance of a task was more variable, potentially questioning the impact of the global compound score. During the unilateral tasks, the pre—PHV Group appeared to use more upper limb, pelvic rotational and ankle strategies, with the post–PHV group obtaining less strategic use of these anatomical regions than circa–PHV group. The circa–PHV group also made greater use of new strategies demonstrating a higher frequency of use of both noticeable and significant valgus than any other of the growth groups.

5.4.1 Seasonal change in unilateral loading task did occur that was limited to landing only.

Single leg landing performance as assessed by compound QASLS score did change during the course of the year but this was limited to circa and post-PHV groups. Studies analysing Single leg landings in comparable age groups have reported a similar result to those presented in this current study. In a descriptive laboratory study on 33 adolescent girls aged 10-13, (Wild, Munro and Steele, 2015) stated that during their adolescent growth spurts, girls demonstrated a change in landing strategy over a 12-month period, although this was limited to evaluation of the hip knee and ankle only.

This supports additional findings which concluded that lower extremity (LE) biomechanics altered across maturation, where post-pubertal knee abduction angles and moments were larger in a sport-specialised group when drop vertical jump performance was tested over a 6-month period. Studies directly pertaining to seasonal variation of NMC measures specifically are limited, seasonal variation in other physical qualities has been demonstrated in youth athletes (Jespersen *et al.*, 2014; Ellenberger *et al.*, 2020; Lloyd *et al.*, 2020). Kinetic and kinematic assessment of youth footballers showed changes (both negative and positive) in jump height, sprint and COD metrics in differing growth groups pre and post-season measures (Morris *et al.*, 2018). The authors attributed the seasonal variation to the maturation stage, with different mechanisms proposed for each group. Furthermore, Emmonds *et al.*, (2020) also reported increases and decreases of the same metric through a sporting season in female youth footballers, with different mechanisms of change postulated for each age group.

Circa-PHV athletes in the present study demonstrated significant differences in compound QASLS scores between P1(start season or school year) and P3 testing for both limbs. Additionally, right limb changes were also observed between P1 (start) and P2 (mid). With compound scores increasing between P1 and P2 and then reducing between P2 and P3 and P1 and P3, suggests that the circa-PHV group has a greater use of strategies between the start and mid-point of the season, but ultimately used fewer strategies to complete the same landing tasks between the start point and P3 testing. Consistent with the present findings, Morris *et al.*, (2018) demonstrated circa-PHV group improvements during speed and CMJ performance. Although not directly measured, the authors proposed that the observed improvements were due to the circa-PHV group being able to capitalise on training-induced adaptations that were enhanced by natural increases in androgen hormone concentrations. Furthermore, Emmonds *et al.*, (2020) also reported physical quality improvements in U14-U16 females pre to mid-season, although these improvements lessened mid-post season. Positive adaptations to training were also proposed as an explanation for changes, however, Emmonds *et al.*, (2020) went one step further by acknowledging that changes could also reflect the natural processes of maturation and growth and that for some athletes any performance changes could have occurred regardless of training.

However further evidence suggests that during the growth spurt, adolescent athletes are likely to demonstrate decreased NMC patterns (Read *et al.*, 2016, 2018; Agresta *et al.*, 2017; Cumming *et al.*, 2017; DiCesare, Montalvo, Barber Foss, Thomas, Ford, *et al.*, 2019). Given the increase in compound QASLS score (and thus increase in the number of strategies required), between the start and mid-point of the year/season, seen in the circa-PHV group in this study. It is possible that the rapid period of growth associated with this maturational (growth-velocity) phase contributed to the initial increase in compound QASLS score, as neuromuscular processes were impacted and the gradual decline in score between P2 to P3 was reflective of an adaptation supported by formalised training and or a growth associated regression and progression in motor skill (Quatman-Yates *et al.*, 2012).

Interestingly, the post-PHV group demonstrated an increase in compound QASLS score through the year, indicating an opposite reduction in the number of strategies required to complete the same landing tasks at the start of the year (P1) compared to P3. Although no significant changes were observed between the start and midpoint of the year, or the mid-point and P3, it is postulated that as growth-velocities are slower in the post-PHV stage than the circa-PHV stage, performance changes would have been slower as it takes longer to progress between 96-100% of predicted adult height (Monasterio *et al.*, 2020). These results are also in line with Morris *et al.*, (2018), who demonstrated smaller decremental changes in CMJ and sprint performances in post-PHV footballers pre and post season compared to the circa-PHV group. Like the adolescent athletes in Morris *et al.*, (2018) paper, it is possible that the decrease in landing performance over the year may be attributable to the accumulation of fatigue over the sporting season and academic year, or that training stimulus did not generate adaptation stimulus in the same way it did in circa-PHV groups.

However, as mentioned in the literature review, movement quality is multifactorial and interacts complexly with additional factors, growth and maturation is only one aspect of several elements that impacts NMC. The seasonal variation displayed during the unilateral task may also have been impacted by changes in training focus in the first and second half of the year (technical to physical, winter sport to summer sport) (Emmonds *et al.*, 2020; Lloyd *et al.*, 2020), or indeed accumulated fatigue both physical and cognitive across the year, as academic demands became more rigorous on the post-PHV cohort. Changes in training focus are not just synonymous with team sports such as football and rugby but occur in both the dance and tennis environments. Although each vocational dance school is slightly different, there are frequent blocks of technical focus in preparation for practical exam periods, followed by a change in focus to performance as repertoire is then learned in preparation for shows of public performances in the latter part of the year. Similar changes in focus are also documented in tennis, between the winter and summer seasons, where those aged 13-14 will begin pro tours and training focus will change over the year as players move from indoors to outdoor settings, and or change playing surfaces from slow clay courts to fast grass ones. Training load, fatigue or exertion metrics were unable to be obtained during this work which might have offered additional insight into the seasonal variation that occurred within the circa and post-PHV groups. Future research should consider the further interactions between changes in NMC, training load and maturational status across a year or sporting season.

When evaluating unilateral task performance by compound QASLS score, no significant seasonal variation was noted during the squatting task or within the pre-PHV group. This result is in contrast to previously proven assumptions within cross-sectional design-studies that squat performance changes are the norm (Barker-Davies *et al.*, 2018), and further highlights the limitations of stand-alone assessment or isolated profiling sessions such as those encountered during pre-season, around the context of seasonal physical quality development. As this appears to be the first investigation that has used qualitative measures to evaluate seasonal variation in adolescent athletes and definitive conclusion as to why there was no seasonal variation observed in squatting but there was in landing is difficult to deduce, an explanation is likely to be within the difference of the tasks themselves. Whilst both the SLS and SLL are frequently used as tools to monitor movement patterns and motor task development (Agresta *et al.*, 2017; Barker-Davies *et al.*, 2018) the motor skills of each task are different (Dawson and Herrington, 2015; Raffalt, Alkjær and Simonsen, 2016).

Landing is an open-chain activity, a discrete task that requires rapid absorption, landing can have a different way of starting and finishing (Estevan *et al.*, 2020), whereas SLS involves a more continuing cyclic pattern with elements of balance (Hutchinson, Yao and Hutchinson, 2016; Agresta *et al.*, 2017). According to a cross-sectional study of 662 children aged 5-18 years, where alternating movements such as landing tend to progress until the age of 18, performance improvements of repetitive tasks such as squatting plateau between the ages of 12-15 (Largo *et al.*, 2001). However, the results like the results in this study were prone to large interindividual variation. Given this, and the fact that there were no significant differences observed in SLS performance within each PHV group, especially the pre-PHV group was considerable and therefore whilst compound scoring of a squat may be stable, the composition of squat performance (as seen in the component score) is highly unique, variable and individualist.

5.4.2 Biological sex did not impact unliteral task performance as assessed by compound QASLS score

Although reports of sex-specific differences in squatting and landing tasks are not a new phenomenon, recent narrative commentary (Nimphius, 2019; Parsons, Coen and Bekker, 2021) regarding observed gender differences in performance beyond biological factors have renewed interest in the issue. No significant sex-specific differences were found between QASLS compound score regardless of task or limb. Evidence regarding sex-specific gender differences in unilateral squatting and landing tasks remains contradictory. Some authors (Hewett *et al.*, 2005, 2006) have suggested substantive deviations in movement patterns between maturing female and male adolescents, especially in females towards advancing maturation. Whereas others, who reports no significant interaction effects of sex during drop-landings (Barber-Westin *et al.*, 2005) or single-leg squatting performance (Agresta *et al.*, 2017) compare to the findings of this study.

It is possible that when performing a unilateral task, adolescent athletes may display sport-specific differences in movement strategies. While no significant effect of sex and unilateral task performance was revealed in this study, it is worth acknowledging that the exploration effect of sex and sporting discipline was limited by the impact of COVID-19 and the number of participants recruited to this thesis. Although participants in this study were involved in other sports, across multiple months of the year, therefore consequently classified as multisport athletes and not individual sport specialised athletes. This is a challenge that is unique to the adolescent researcher. Within the adult literature, the majority of elite adults will have advanced towards one specialised sport, meaning inferences regarding the effects of sex and sport are likely to be less ambiguous. Unlike adults, or early specialisation adolescents, classification to one sport for adolescents that continue to diversify is likely to be less definitive.

It was beyond the scope of this study to further investigate the idiosyncrasies of early specialisation versus diversification athletes, as current classifications and definitions of each remain ill-defined (Buckley *et al.*, 2017); however precursory literature suggests that landing mechanics may not be influenced by sport specialisation status (Peckham *et al.*, 2018; Kliethermes *et al.*, 2020). The preclusion of sex and sporting discipline from this multisport participant study therefore isn't thought to impact the observed differences in PHV groups and task performance, however caution is advised generalising these findings to different adolescent populations such as early specialisation athletes. As such future research directions may wish to explore in larger participant numbers the effects of sex and sport on unilateral movement strategies in adolescent athletes from early specialisation and diversification backgrounds, to determine sex-specific factors in conjunction with environmental factors beyond the biological classifications, that might impact adolescent injury risk factors.

5.4.3 QASLS components had different prevalence at a different percentage of predicted adult height

To add additional insight into unilateral task performance over a year or sporting season further analysis of the composite QASLS score was undertaken by reviewing the component elements of the tool concerning growth and maturation status. It was hypothesized that pre and circa groups would demonstrate greater variability of strategies which were evident in the greater compound scores. The results of this study partly support this statement, as contrary to original thoughts, SLS performance did not significantly change over the course of the year, there were differences between PHV groups and a trend that unilateral task performance improved with those at the higher end of PAH% using fewer strategies that those at lower PAH%.

Previous data indicated that movement patterns are likely to be affected during an adolescent growth spurt (Quatman-Yates *et al.*, 2012; Difiori *et al.*, 2014) and therefore data demonstrating information around how movement patterns may be different at different phases of growth is useful information for practitioners designing rehabilitation or conditioning programmes. The most noticeable differences in strategies between growth groups were observed in the upper limb, knee and ankle (table 5.5 and 5.6), which may be indicative of progression and regressions of motor skill performance. Overall, the selection of each component varied according to PAH% and therefore each component element is discussed separately.

Arm strategy

An upper limb strategy was predominantly used within the pre and circa-PHV groups in around 65% of those between 60-84.9% of predicted adult height during both unilateral tasks, and in around three-quarters of those during squatting and half during landing that was between 85-96 PAH%. Whilst an arm strategy was required by approximately 50% of those in the post-PHV group on the left limb its use had dropped by half to 35% during squatting and in only a quarter of those at >96 PAH%. It is believed that this is the first paper to consider the relationship of maturation on upper limb performance during unliteral tasks, and due to methodological restrictions (see Chapter 2 and Chapter 3) are usually applied to the upper limb during previous squatting and landing research. Comparisons to other papers and definitive explanations around the upper limb use in maturation cannot be conclusively offered at this time.

Plausible explanations for the widespread UL use in pre-pubertal groups and a slight increase in the circa-PHV phase might include its use as a balance aid, an additional visual queue, or as part of a prolonged motor response described as the parachute reflex (Jaiswal and Moranka, 2017; Bennett, Lashley and Golden, 2020). The parachute reflex emerges in infants who reflexively extend the upper limb into flexed or abducted positions as an infant tries to catch themselves from a fall or ventral suspension (Jaiswal and Moranka, 2017). As seen with the adult participants in chapter 3, it is possible that the unilateral tasks completed by this studies participants, notably the pre-pubertal athletes were interpreted as a fall, which elicited the deployment of an upper limb strategy through the incitement of a primitive reaction associated with the parachute reflex. Between the ages of 6-9 years posture and balance-related skills are still emerging (Difiori *et al.*, 2014), and whilst those aged 10-12 have shown better mastery of this skill, this finding may represent temporary reductions in balance ability during the adolescent growth spurt (Oba *et al.*, 2015). Whilst the debate around balance development being linear or non-linear remains, changes in postural stability and postural orientation during maturation have been shown to occur (Sowa and Meulenbroek, 2012). Due to the changes in the relative location of the centre of mass to an athlete's interaction with their space that also occur during growth, it is not unreasonable to infer that the use of upper limb strategy may impact a youth athletes' relationship with their base of support and is part of the wider somatosensory process as the central nervous system adapts during the maturational process.

The CNS also regulates balance through visual information, known as sensory integration, the ability of the body to transfer that visual information to stability continues to develop throughout adolescence (Assländer and Peterka, 2014). Younger children also tend to struggle with postural stability when they are subject to multiple conflicting sensory queues (Quatman-Yates *et al.*, 2012). It might be that movement of the upper limb is an additional queue and that by adopting a stiff-arm strategy, younger children were able to limit the processing of information of UL location in relation to the body in space, reducing the noise in the CNS and an improvement in the postural control (Quatman-Yates *et al.*, 2012; Sowa and Meulenbroek, 2012; Assländer and Peterka, 2014; Difiori *et al.*, 2014).

Although both these explanations remain somewhat hypothetical constructs, this data highlights the importance of the upper limb and further demonstrates how its interaction with complex whole movement patterns is not yet understood. Methodological consideration of the upper limb is vitally important as research in this fields progresses, as due to current methodological restrictions on task instruction and restricted UL position, previous evaluation has not been possible. Practically there results also reflect the non-linear nature of growth and further demonstrate the need to consider maturation as a confounding factor in upper limb research.

Trunk Alignment

During both unilateral tasks, a gradual decline in trunk use towards the mature state was observed but was still evident in 44-57% of the post-PHV group during squatting and 60-68% landing. During and following periods of rapid growth, the sudden alterations in the relative position of the centre of mass in space and increased in overall mass have been shown to make trunk control more difficult during dynamic tasks (Myer et al., 2008). Furthermore, growth of body segments has been proposed to occur distal to proximal, with the trunk and chest frequently the last body segment to mature, with a wide variation of trunk growth spurt timing (Malina, 2014). This corresponds to the findings of this study, where the selection of a trunk strategy remained through most maturational stages and was also more pronounced during the more dynamic landing task in the older athletes. This information is useful for practitioners and coaches as it further reflects not only the variation in growth spurt timing but the variation in the timing of body segmental growth spurts. During landing centre of mass deceleration depends on control of body mass over the limb, with accelerated increases in the centre of mass being suggested as an impactive factor on body position control (Crossley *et al.*, 2011). (Hewett and Myer, 2011) further connected this pattern to injury risk. Following the results of this, it is suggested that practitioners have a greater awareness of movement quality of the trunk not only with the circa but post-PHV stages of growth if they wish to further evaluate injury risk.

Pelvic Strategies

The participants in this study did not use the pelvic strategies of "loss of the horizontal pelvic plane," increased pelvic tilt or rotations in the same way during the two unliteral tasks. During both tasks, a gradual increase in the loss of horizontal pelvic plane occurred, with the pelvic plane being the most utilised strategy in the post-PHV group (84-91%). Pelvic tilt and rotation differed between PHV groups during both tasks, with around 50% of pre-PHV athletes requiring this strategy during squatting and approximately 30% during landing, comparative to the less than 15% during post-PHV group. With respect to the use of pelvic tilt and rotation, the observed decrease in values through maturation may be explainable by the direct association to spinal growth and occurrence of pelvic incidence and pelvic tilt during childhood, which is known to stabilise at maturity (Sanders, 2015). The posterior spinal inclination is at its greatest around the peak of the growth spurt, with an increase in posterior sheer also being associated with decreases in rotational stiffness and control (Schlösser *et al.*, 2015). Therefore, the higher use of a pelvic strategy through pre to circa phases of growth is more likely, as seen during squatting in the participants in this study (Table 5.4).

Whilst the gradual increase of horizontal plane loss is harder to explain, this observation may be closely related to spinal changes that impact tilt and rotation and the later development of the trunk. The quality of a movement pattern is mutually dependant on what is occurring through the whole kinetic chain process, where changes and alterations in 1 segment may well impact the other (Hewett and Myer, 2011). Therefore, the continued use of the pelvic plane may also be reflective of the continuing trunk development into post-PHV stages, as a compensatory response for alteration in centre of mass height or alterations in hip and trunk strength. It remains difficult to refute or support these claims as there appears to be no literature currently that has investigated interactions between maturation, trunk and hip strength and landing performance. This may be an interest in future research.

Thigh Strategies

When evaluating hip adduction very small numbers of participants utilised this strategy during squatting or landing. Not only does this suggest that changes in hip adduction through a year are not the norm, but also its absence of use within this cohort suggest that throughout maturation adolescent athletes do not use hip adduction as a strategy to complete either task. This was also reflected in the cross-sectional results in Chapter 4 (4.4.2-4.4.3) with athletes demonstrating no significant differences in 2D values of hip adduction angles. The relationship of hip adduction in an adolescent cohort also remains questionable. This is in contrast to the adult literature, where hip adduction has been shown as a key strategy in adults to stabilise the pelvis (Maykut *et al.*, 2015; Herrington *et al.*, 2017; Barker-Davies *et al.*, 2018). Subsequently, the difference in findings regarding the use of hip adduction as a movement strategy in youth athlete's comparative to an adult populations, suggests that profiling tools and movement tasks that evaluate hip adduction might not be a priority or correspond as an injury risk factor in quite the same way.

The use of the NWB thigh also gradually declined during maturation but remained a prevalent strategy in up to 60% of the post-PHV group during squatting and 85% during landing. Kinematic assessment of the none stance leg during the SLS in adults has demonstrated significant biomechanical effects at the trunk and pelvis, with large effect size alterations seen in anterior tilt and pelvic drop when the none stance leg was not maintained in neutral. Suggesting the none stance leg challenged the neuromuscular system differently (Khuu, Foch and Lewis, 2016). Whilst this has not been substantiated in an adolescent cohort or during landing, that as the CNS continues to develop throughout adolescence (Quatman-Yates *et al.*, 2012; Difiori *et al.*, 2014; Schlösser *et al.*, 2015) might further explain why athletes select this strategy throughout the maturational process.

Interpretation of these results indicates that the inability to maintain the none-stance leg in neutral could be a response to the altered trunk and pelvic strategies, associated with normal maturational processes. Practitioners can use this knowledge to better inform any movement pattern differences that occur during the unilateral tasks. This should improve future profiling, as restricting the position of the none stance leg may affect the trunk and pelvic strategy or vice versa. Maintenance of the NWB leg, in neutral, should not be expected in a pre-PHV cohort, results also infer that control of the NWB leg may not occur till very late in the growth process.

Knee Valgus

As with the exploration of 3D and 2D parameters, current maturational papers focus predominantly on the knee relative to other body segments. Despite the convergence on knee valgus the majority of papers evaluated knee valgus performance within the bilateral position (Read *et al.*, 2016; DiCesare, Montalvo, Barber Foss, Thomas, Ford, *et al.*, 2019) or within chronological not maturational bandings (Agresta *et al.*, 2017; Räisänen *et al.*, 2018a). Generally, the results of this study agreed with the wider literature that knee valgus is more prevalent during growth. Noticeable valgus was present in over 90% of those between 85-96% of PAH% during squatting and 48-68% during landing. With 40% of circa-PHV athletes demonstrating that valgus as significant, comparative to under a quarter of participants in the other growth groups. However, these results are in contrast to the premise that dynamic knee valgus is especially adverse.

Instead, this data set with the increased use in nearly every squat repetition by the majority of those within a circa-phase lends itself to the premise that during a spurt of growth neuromuscular knee control may, in fact, be regressive rather than deleterious during circa-PHV phase (Quatman-Yates *et al.*, 2012) as the body recalibrates itself in response to growth. As previously mentioned the progression through the post-PHV phase (96-100 PAH%) typically takes longer to advance (Monasterio *et al.*, 2020) and might account for the 53-64% of prevalence still observed in the later stages of growth in this participant group. Injury data was not collected alongside this study (referred to in section 5.5), however, participants were excluded from testing if they presented with a current or on-going injury. It may also be inferred, that as no participant withdrew from the study due to knee injury, future research should investigate knee valgus and its inter-relationships with additional factors of risk (such as anatomical structures, the menstrual cycle, age of training exposure), as knee valgus as a stand-alone measure appears to be limited as an informative measure.

Ankle Strategies

During squatting whilst less than 30% of the circa-PHV group utilised either a touchdown strategy of the NWB or stance leg wobbling, over three-quarters of those at less than 85% of PAH% demonstrated the use of the NWB leg, and at least a third demonstrated a wobble strategy. The pre-PHV group also used greater amounts of ankle strategies during landing than the circa and post-PHV groups, but less than was observed during the squatting task. This agrees with previous findings that concluded children with under-developed ankle strategies have less anterior-posterior directional control and a potential lack of ankle muscle stiffness (Quatman-Yates *et al.*, 2012; Estevan *et al.*, 2020).

This study followed the documented patterns of the declining frequency of ankle strategy use through the maturational groups (Monasterio *et al.*, 2020). This also follows the assumptions that the lower limb spurt precedes the trunk (Difiori *et al.*, 2014; Agresta *et al.*, 2017; Cumming *et al.*, 2017) and that PHV of the ankle, calf and lower portion of the lower limb predominantly occurs pre-85% of PAH%.

Speculatively, this is useful visual information for a practitioner. As an athlete who is observed to have an improved ankle strategy with increased ankle stiffness and less reliance on the NWB leg may well be a sign that an athlete is progressing into later maturational stages, and further shows the importance of providing progressive options around the time of accelerated predicted adult height when planning a rehab or conditioning programmes. The current results of this study indicated that unilateral task performance, as evaluated by QASLS score, will show little but none significant change in squat performance over a sporting season, regardless of the maturational phase.

However, changes in landing performance are to be expected over the course of a season in those that are in the end stages of growth, and first and second half seasonal variation may well be present in those going through a growth spurt. Whilst within an individual and within task performance are hugely variable this study shows compound and component scores are different according to PAH%. Selection of component strategies appears to follow the distal to proximal patterns documented throughout growth and maturation (Malina, 2014; Cumming *et al.*, 2017), with a gradual decline in the foot, ankle and lower limb strategy use as PAH% advances. The decline in foot and ankle strategy appeared to coincide with those participants who progressed into 85-96 PAH%, an example of developing unilateral stance.

The sharp increase in reliance in dynamic knee valgus strategies coincides with those at 85-96 PAH%, the suggested moment when leg length PHV and motor skill regressions are postulated to occur (Quatman-Yates *et al.*, 2012; Malina, 2014). Prolonged use of a trunk strategy into circa to post-PHV group (85-100 PAH%) also coincides with current theories in the literature (Myer *et al.*, 2008; Dingenen, Blandford, *et al.*, 2018) around prolonged challenges with trunk control due to the centre of mass changes during and following rapid growth phases. Due to this, and the large variations noted within individual performances of unilateral tasks, the use of PAH% to classify adolescent participants when utilising and researching movement quality seems apt.

5.5 Strengths and limitations

There are inherent limitations in this study. First maturation was classified using non-invasive methods of percentage estimate of adult height (PAH%). Whilst it is acknowledged that radiographical measures of skeletal age and tanner stage are the gold standard of the biological and maturational stage (Wild, Munro and Steele, 2015; Agresta et al., 2017). Due to the field-based nature and ethical considerations of this study, whilst the non-invasive methods where the contextually correct method of anthropometric data collection, the potential measurement error of these methods has to be acknowledged. Although this could be preserved with the data set, all anthropometric collection was completed by the same researcher with the same equipment to mitigate against this.

Secondly, whilst all participants where part of an organised sporting club (i.e. training sessions were structured, access and participation with formal strength and conditioning and rehab sessions was undertaken), there was no influence over the configuration of these sessions as each organisation designed and delivered their own content. Therefore, training content and exposure to load could not be collected during this work. Whilst training load as a causative factor to injury risk is not the panacea it once was (Maupin et al., 2020), to better understand the interactions between movement quality, maturational status and injury risk. Future research should look to include measurements of training load or a training intervention to better inform mitigation of risk, and to further establish how rehab or conditioning training impacts performance above that noticed with normal maturation and growth.

Although training load has been identified as a direction for future research, its omittance from this study isn't thought to limit the observed changes in unilateral landing performance or differences observed in task performance between PHV groups.

One of this studies strengths was the selection of a longitudinal methodology, that aimed to advance the cross-sectional data extraction in Chapter 4. Whilst data from the previous chapter demonstrated unilateral task performance differences at generalised growth levels, Chapter 5 data has improved this by further evaluating that performance over a year. Whilst this is thought to be the first study to consider maturational status, seasonal variation and unilateral task evaluation by a qualitative method. Additional longitudinal monitoring over subsequent seasons or academic school years would further evaluate individual maturational effects to completions of adult heights.

The addition of the mid-year testing point has furthered work that has captured only pre and post-season measurements, by highlighting the non-linear development, and potential phases of regression that occur during the season. Although this is observed with caution due to bringing forward of phase 3 data capture, time frames between P1 and P2, and P2 and P3 were not equal and there is no guarantee that observations in data at the postseason collection point would have yielded the same results. It is argued however that proof of concept has been established enough for additional test points to be included in the season. This would further add to the training load and fatigue effects investigation, which would be key to prospective injury risk studies.

A final strength of this work, is the development from analysis of singular biomechanical patterns, instead of focusing on many component metrics within an individual pattern. This work has attempted to evaluate common unilateral patterns of movement, in a way (qualitative) that has not been extensively studied in adolescence. Mechanisms of injury and injury risk factors remain multifactorial (Monasterio et al., 2020). In the same way, singular biomechanical metrics have poor associations with injury risk and injury prediction, other elements beyond NMC or maturation, such as the addition of training load must also be taken into consideration moving forward.

5.6 Conclusions and Future Directions

This study has evidenced that when evaluated by the QASLS qualitative tool, composite scores single-leg squat performance did not change over the course of a season regardless of maturational status. Performance of a single leg landing task did change between the start to mid and mid to end phases of testing for those who were between 85-96 PAH% and start to end phase differences were noted in those between >96-100 PAH%. Whilst within-group compound QASLS scores appeared to be stable. A general declining trend in compound score relative to advancing maturation was observed throughout the season. Intra-individual variation of task performance remained large as evident in the component evaluation of QASLS scoring. When evaluating body segment components to comprise the composite score, strategy selection to complete unilateral loading tasks appear to follow a pattern of PAH%. Use of ankle and maintenance of unilateral stance (such as arm and touch down strategies) appear to occur more frequently in the pre and circa groups or at an earlier PAH%. Use of a knee strategy appears to be present in most of those classified in 85-96% of predicted adult stature, the band most associated with rapid growth. Trunk alignment strategies appear to be present throughout the growth process although there is an observed trend of declined use through the growth process. This is a notable finding that further infers the inclusion of multiple biomechanical factors in favour of evaluation of the whole pattern.

Overall this data set indicates landing performance changes during the course of a season, with probable links to maturation, and that component selection to complete either unilateral tasks is affected by PAH%. Highlighting the various changes that occur in movement quality due to maturational related changes that can occur in the NMC system. General outcomes from this study highlight the need for practitioners that design and implement profiling tools and movement tasks for adolescent athletes, to incorporate measures of maturation to identify the growth spurt status of athletes especially if they are evaluation NMC. By considering the wider context of growth and maturation in relation to movement strategies, embraces the complex systems approach required to complete further prospective injury risk research in this cohort. Improving understanding of means of monitoring and profiling to mitigate injury risk in adolescence is important due to the biopsychosocial, performance and development impacts injury has on this population.

Accordingly moving forward with this study, future prospective studies pertaining to injury risk within an adolescent population, can effectively evaluate movement quality of unilateral tasks via qualitative measures cross-sectionally or longitudinally, should they incorporate maturational state. In terms of task selection longitudinally, unilateral landing tasks appear to provide better sensitivity to seasonal performance variation. Whilst this does not appear to be replicated in unilateral squatting, potentially due to inherent large movement variation. The monitoring of movement quality via SLS remains advantageous as a feasible practically applicable tool, if the limitations of its use to cross-sectional evaluation of movement strategies for task completion, and insight into potential information on individual performance influenced by maturational status are acknowledged. This can better inform the direction of travel of injury rehabilitation and returning to train programming for practitioners.

Following the lack of statistically significant findings in this study regarding effects of sex-specific differences and the requirement for greater participant numbers for analysis of sex on sport and PHV group. Future research should focus on prospective studies with larger participant cohorts to further explore the complex systems approach context, to promote greater understanding of the relationships of profiling, maturation and injury risk, whilst acknowledging biological sex-differences but honouring a better more substantiated narrative regarding gender performance risk.

Chapter Six

6.0 The effect of a rater training educational piece on inter-rater consistency for a Qualitative Assessment System (QASLS)

Aims:

1) Identify the levels of agreement between non-specialist/specialist raters pre and post an educational intervention

2) Determine if formal training via an education intervention improves consistency to a criterion rater

6.1 Introduction

Movement assessment and evaluation of movement quality is evolving from isolationist muscle, range or joint evaluation to evaluation of movement patterns as a whole to endeavour to further understand regional interdependence or, the interactions of each body segment with another (Butler *et al.*, 2010). Whilst quantitative analysis evaluates and characterises movements numerically, qualitative analysis aims to analyse and depict movements as a whole system or pattern, as in terms of sporting performance the way somebody moves or the quality of their movement echo's elements of performance that might not be captured by measurements concerning height, distance or frequency (Ageberg *et al.*, 2010).

Due to the limitations of three dimensional (3D) technologies and the feasibility regarding practical application in terms of replication of 3D movement analysis in the clinical/practical environment, profiling tools and systems that encircle a more holistic approach via consideration of the whole kinetic chain through qualitative evaluation have gained traction within the clinical arena. As the requirement for assessment that captures simultaneous multiple aspects of the function becomes more evident, qualitative evaluation is becoming more prevalent as a simple, more cost-effective (Dar, Yehiel and Cale' Benzoor, 2019).

As discussed in chapter two, there is a spectrum of rater reliability studies on both kinematic and kinetic markers, with previous critics proposing that a primal limitation to the qualitative method is the greater subjectivity seen with interpretation by raters and requirements of high levels of movement assessment skill for task evaluation (Dar, Yehiel and Cale'Benzoor, 2018). Intra-rater reliability (the consistency of 1-person measurements) generally presents with better reliability than inter-rater reliability (the consistency of measurement between different people) (Burr, Pratt and Stott, 2003) and rater variability, especially around movement quality has always been described as an influential source on measurement error. When assessing any construct reliability from consistency, consensus or measurement estimates, the determination of intra-rater reliability before inter-rater reliability is important, although established intra-rater reliability does not guarantee established inter-rater reliability (George, Batterham and Sullivan, 2003; Stemler, 2004; Batterham and Atkinson, 2005).

Chapter Three established intra-rater reliability of the Qualitative Assessment of Single Leg Loading (QASLS) tool as excellent (PEA% = 0.90-1.0, κ = 0.85-1.0), however, the inter-rater reliability was substantially lower, with a noticeable difference in agreement between non-specialists and the specialist rater, despite relatively good scores between the non-specialists. Conversely, literature has demonstrated novice or non-specialist scorers having equal or better levels of agreement than expert or specialist raters (Baer *et al.*, 2003; Padua *et al.*, 2009; Minick *et al.*, 2010; Shultz *et al.*, 2013; Whatman, Hume and Hing, 2013; Weeks, Carty and Horan, 2015; Cuff, Palmer and Lindley, 2018) in other qualitative methods such as the Tuck Jump Assessment (TJA), Landing Error Scoring System (LESS) and Functional Movement Screen (FMS).

The use of the FMS in collegiate athletes indicated fair reliability amongst less experienced raters but poor reliability in those with 2 or more years' experience (Shultz et al., 2013). Inadequate inter-rater reliability for ordinal measures via descriptive scales was demonstrated when specific elements of segmental scoring were considered, although this improved to clinically acceptable values when a compound overall score for the same method was selected (Chmielewski *et al.*, 2007). This was also in agreement with later work by Poulsen and James, (2011) where compound scores of an ordinal scale exhibited good to excellent inter-rater reliability scores, but individual ordinal scale measures demonstrated inadequate levels for clinical use.

Differences between speciality level and compound score vs components score have also been shown within an NHS setting, where non-specialist MSK physiotherapists demonstrated excellent inter-rater reliability for FMS compound score and moderate-excellent for FMS components comparative to the good and poor-excellent respectively for the specialist practitioner group (Cuff, Palmer and Lindley, 2018), as well as within mobility assessments where staff grade physiotherapists achieved higher levels of reliability than senior physiotherapists (Baer *et al.*, 2003). Higher levels of rater agreement have been demonstrated by in-experienced raters during a visual qualitative analysis of an SLS (Ageberg *et al.*, 2010), and between experienced and student MSK physiotherapists (Weeks, Carty and Horan, 2012) following extensive and no rater training.

Whilst the majority of authors acknowledge the differences between novice and specialist raters, most do not expand on specific differences between these groups as to why these differences may be evident, the rationale for low agreement between raters is frequently vague, and whilst most authors advocate the use of clear, simple standardised instructions with adequate levels of rater training (Ageberg *et al.*, 2010) to reduce the ambiguity of scoring by raters (Shultz *et al.*, 2013), the majority of research papers do not elude to what an educational approach to qualitative assessment might contain. Rater training is commonly proposed as a method for countering rater variability to improve rater assessment quality, whilst the majority of practitioners are likely to receive some basic levels of movement analysis by visual observation during their academic formal training (Chmielewski et al., 2007), there is little to no research regarding the nature of training programmes for qualitative assessment.

It has been proposed that a more comprehensive and systematic education around movement assessment improve inter-rater reliability levels, whilst some authors have suggested a few hours of direct training (Padua *et al.*, 2009) to more extended periods of 20 hours (Teyhen *et al.*, 2012) which has resulted in the conception of more extensive formal training courses (noticeably with FMS). This in itself might be limited to clinical practice due to increased associated time and financial cost. However other authors have used more reduced periods of rater-training of up to an hour with great success (Onate *et al.*, 2010; Everard, Lyons and Harrison, 2018), suggesting that the delivery of more explicit guidelines via rater-training is possible in short periods of time. As differences in rater-reliability have been shown across multiple disciplines, in several sectors (Private, sporting, NHS) at different levels of training from students through to expert, it appears that researchers should aim to establish education and training programmes that are less concerned with a raters overall expertise level as a practitioner and focus on increasing rater consistency to reduce measurement bias and increase the application of understanding.

Concerning the QASLS tool specifically, only two papers have considered inter-rater reliability (Almangoush, Herrington and Jones, 2014; Herrington and Munro, 2014) and both were limited to expert raters (12 years of experience) based on both years of experience and academic qualification, and therefore the level of agreement around the QASLS tool by raters of different experience either academic and or practical remains unknown. Each component of the QASLS tool is based on specific previously identified risk factors for the lower limb. Currently, there is no formal training available and whilst there is a concise operational definition (figure 6.1), there is no set standardised interpretation. Whilst this is a considered strength of the tool as it allows the individual rater to define their own definition of the proportion of each component, it does leave room for rater variation.

The influence of rater education vs rater experience in terms of rater-reliability on general qualitative assessment tools remains highly elusive and the level of previous experience required of a clinical test in relation to obtaining consistent measurements across the qualitative movement assessment literature appears to still be unknown.

Across sports science and physiotherapeutic clinical practise, greater attention is being placed on visual observation and analysis of movement via a complex systems approach.

Qualitative analysis of single leg loading

Date: **Patient:**

Condition: **Left** **Right** **Bilateral**

QASLS	Task: Single leg squat Single leg step down Single leg hop for dist	Left	Right
Arm strategy	Excessive arm movement to balance		
Trunk alignment	Leaning in any direction		
Pelvic plane	Loss of horizontal plane		
	Excessive tilt or rotation		
Thigh motion	WB thigh moves into hip adduction		
	NWB thigh not held in neutral		
Knee position	Patella pointing towards 2nd toe (noticeable valgus)		
	Patella pointing past inside of foot (significant valgus)		
Steady stance	Touches down with NWB foot		
	Stance leg wobbles noticeably		
	Total		

Figure 6.1 Example of QASLS Tool

understanding and aiming to improve rater agreement around movement quality is a fundamental requirement towards the building of robust, standardised movement analysis approaches. There is an ever-growing need to establish reliable and valid movement assessment tools that can capture multiplanar multifaceted aspects of whole movement patterns. If movement assessment tools are to be widely adopted for maximal practical utility, they need to be easily administrable within the practical environment to large groups, be comparable between multiple practitioners, suitable for multi-centre use and require minimal rater training time. The QASLS tool is a relatively simple tool that has high intra-rater reliability and is sensitive and specific in certain components (Trunk, Hip and knee) that are associated with injury risk factors for the lower limb, and therefore may provide practitioners with an appropriate movement assessment tool within the practical setting for evaluation and enhancing unliteral movement tasks.

The research aims of this study were to determine levels of agreement between novice and expert raters pre and post an educational intervention around rater training, and to determine if formal training improved consistency to a criterion rater. It was hypothesised that levels of agreement would be different between non-specialist and specialist raters, and rater training would improve consistency in both groups. In addition to previous research relating to the QASLS tool, this study would evaluate agreement and consistency between a larger number of raters.

6.2 Method

6.2.1 Participants

An online random number generator was used to select 4 participants from a larger pool of 85 participants that had already completed the study following the methods documented in Chapters 3 and 4. Each participant had been videoed completing 5 repetitions of the single-leg squat task from the frontal and sagittal plane, video recordings were edited so frontal and sagittal could be viewed simultaneously by a rater. Participants were allocated a second research number (1-4) for this section of the thesis. The participants had already been scored previously by the lead researcher (GP) and these score profiles were used as the criterion standard.

6.2.2 Raters

A convenience sample of 20 elite sports physiotherapists was approached via email within a high-performance sports institute, 13 participants contacted the researcher expressing an interest to take part, 12 (6 male 6 female) went onto complete the educational piece following the withdrawal of 1 participant due to increased workload and inability to commit to both analysis sessions. Participants met the inclusion criteria (Table 6.1) and were allocated to either the non-specialist or specialist cohort depending on their self-identified level of experience with the QASLS tool as determined at analysis session one. Based on previous research (Shultz, *et al.*, 2013) that has evaluated rater experience in other qualitative tools those with less than two years' experience with the tool were classified as non-specialist raters and those with more than two years' experience were classified as a specialist. Raters had varying levels of clinical experience, educational level and experience with the QASLS tool (Table 6.2).

Table 6.1 Inclusion and exclusion criteria for raters

Inclusion criteria	Exclusion criteria
Expression of interest and ability to partake in both aspects of analysis	Non-Sports Institute employee
Employee of Sports Institute	Unable to access both testing sessions and educational piece training
Non-specialised according to QASLS experience < 2 years	Non-Physiotherapy discipline
Specialist according to QASLS experience > 2 years	

Table 6.2 Comparison of raters who scored QASLS of all 4 athletes to establish rater reliability

Rater	Group	Rater Description	QASLS Experience	Average of total scores Pre-Education	SD	Average of total scores Post-Education	SD	Difference from criterion rater Pre-Education	Difference from criterion rater Post-Education
Criterion	*Criterion*	*MSc Physiotherapist co-conceiver*	*5 years*	*7.75*	0.8	N/A	N/A	*0.00*	*0.00*
1	NS	BSc Physiotherapist 6 yrs' experience	Up to 1 year	7	2.6	8	0.0	-0.75	+0.25
2	NS	BSc Physiotherapist 6 yrs' experience	Up to 1 year	5.5	1.7	7	0.8	-2.25	-0.75
3	NS	BSc Physiotherapist 8 yrs' experience	Up to 1 year	6.5	1.7	7.75	0.5	-1.25	0.00
4	NS	MSc Physiotherapist 10 yrs' experience	1 year	5.25	2.1	7.75	0.5	-2.5	0.00
5	NS	BSc Physiotherapist 13 yrs' experience	1 year	7.25	0.8	9.25	0.5	-0.50	+1.5
6	NS	MSc Physiotherapist 8 yrs' experience	1-2 years	7	1.5	8	0.8	-0.75	+0.25
7	S	MSc Physiotherapist 22 yrs' experience	>5 years	4.75	1.0	7.25	1.7	-2.25	-0.50
8	S	MSc Physiotherapist 11 yrs' experience	2-5 years	6.75	1.0	8	0.8	1.00	+0.25
9	S	MSc Physiotherapist 18 yrs' experience	2-5 years	4.5	1.3	6	0.8	-3.25	-1.75
10	S	BSc Physiotherapist 12 yrs' experience	2-5 years	6.25	1.8	7.75	0.5	-1.50	0.00
11	S	MSc Physiotherapist 17 yrs' experience	2-5 years	6	0.8	7.75	1.0	-1.75	-0.50
12	S	MSc Physiotherapist 8 yrs' experience	>5 years	7	0.5	8	0.8	-0.75	-0.25

NS – None Specialist, S – Specialist, SD – Standard Deviation

6.2.3 Rating Session Protocol

Part One

Once raters had consented to partake, 24 hours after online consent had been obtained, they were emailed an online link to a google form (Table 6.3). Raters were asked to complete some basic information confirming their discipline, qualification level and experience (if any) with the QASLS tool. The second part of the form contained a PDF copy of the QASLS tool scoring sheet as a visual reminder for raters, raters were instructed to watch the 4 videos and complete the digitised version of the QASLS form. Videos contained both front and sagittal views, and raters were allowed to watch the videos an unlimited amount of times, however, once they had submitted the form they were no longer allowed to view the initial videos or their scoring. Raters were provided with basic instructions that are currently provided with the tool, which consists of concise operational definitions for each component. Raters were given one week to complete the forms if they had not completed within 5 days a reminder email to complete was sent. All raters had replied by day 7.

Part Two

Raters completed two testing sessions three weeks apart. A 21-day period was given to reduce the likelihood of participants recalling previous video performances which could have biased results. On the 21st day following completion of their initial form, raters were sent an additional google form (Table 6.3) that contained the training session screencast and additional videos to be scored. The screencast lasted approximately 30 mins and consisted of an introduction to the QASLS tool, the dichotomous scoring process, and verbal and video examples of each of the 10 components that comprise the QASLS tool. This allowed raters the opportunity to gain familiarity with the QASLS tool and potential participant strategies. The same four videos from part one was re-randomized in order by the same online generator, after the educational screencast raters then undertook their second video scoring session. Once a rater had completed a form, they did not have the option to re-review their form or videos. This ensured raters were blinded to their previous scoring. As raters each received their own link they were also blinded to the scores of each other.

Table 6.3 Links to Part One and Part Two google forms

Google Form One *https://docs.google.com/forms/d/e/1FAIpQLSceM2qwvoDkMlGe3B70D1vKQ70Dzn_NV00ACCbmrAky06yAZQ/viewform?usp=pp_url* *Google Form Two* *https://docs.google.com/forms/d/e/1FAIpQLSdiDAqBSpJN26CbkCozK6a5yfxN4ub5P8zeIAlshKCAhGnnQ/viewform?usp=pp_url*

6.2.4 Statistical Analysis

The levels of agreement between specialist and non-specialist raters of compound QASLS scores pre and post-education intervention QASLS compound scores were assessed using Bland-Altman and box plots. Normal distribution was assessed via the Shapiro-Wilk test. Due to the low distribution of scores, between-group differences were determined via Mann Whitney U. Due to the ordinal nature of the individual QASLS components, levels of agreement were established across all raters for each independent component via Kendall's W and percentage of exact agreement (PEA%). Where interpreted according to Kendall's W concordance degree scale, where 0 = no agreement, 0.1-0.29 weak agreement, 0.30-0.59 moderate agreement, 0.60-0.99 strong agreement, 1 = perfect agreement) (Moslem *et al.*, 2019).

To determine the level of consistency between rater scores to that of a criterion score pre and post-education intervention, for compound QASLS scores mean and standard deviations (SD) for the total score for all raters was calculated. To establish concordance of the individual QASLS components to a criterion rater average, Spearman's (R) correlations were calculated both pre and post-education intervention. Differences between rater scores and the criterion score pre and post-education intervention were analysed to determine distribution changes, Mann Whitney U test was then conducted to establish any significant differences between rater groups in scores pre and post-education. A p-value of 0.05 has been used to determine significance.

The criterion score was created by two researchers who co-conceived the tool and designed the education piece (GP and LH) to determine compound and component scores for each athlete. Data were analysed using SPSS 25.0 (SPSS Inc, Chicago, IL, USA) and via custom made spreadsheet (Microsoft Excel Version 16.16.22).

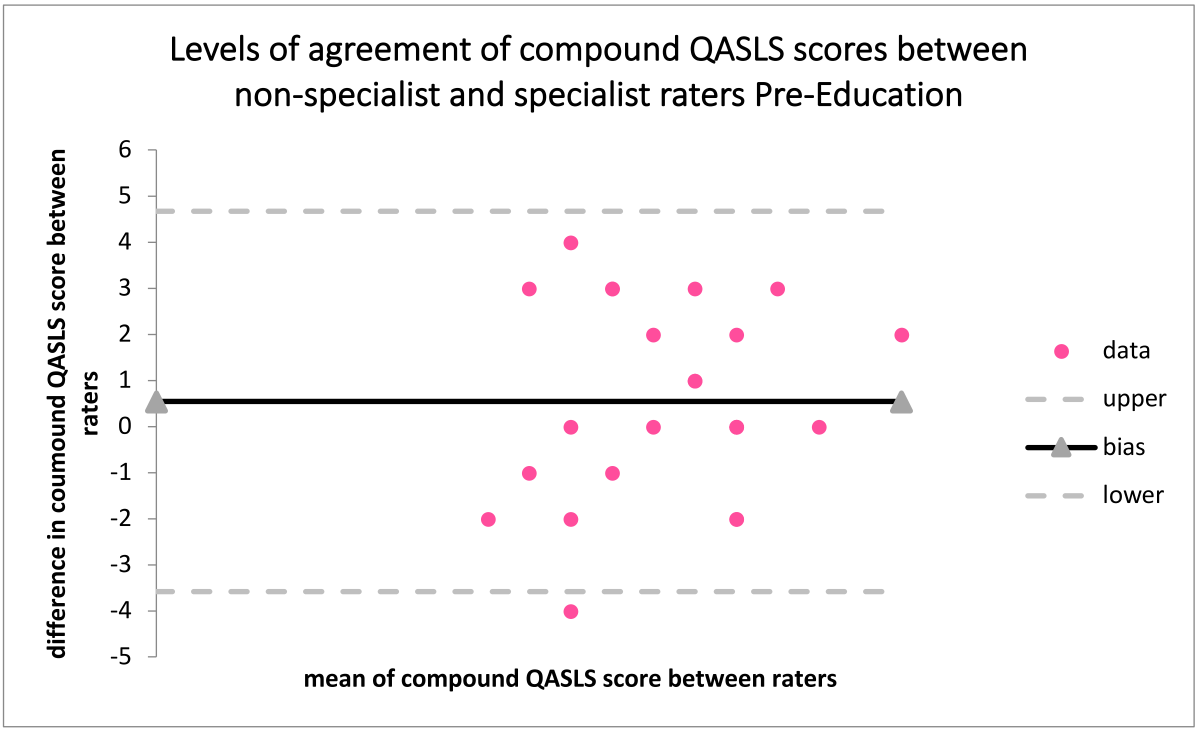
6.3 Results

In total 12 raters scored twenty single-leg squats via compound QASLS score. For each QASLS component, whilst data were normally distributed (as shown via Shapiro-Wilk test) for the specialist group distribution was low, in addition, it was none normally distributed across the non-specialist group and therefore all data was treated non-parametrically. QASLS compound scores for all participants ranged from 3-10.

Examination of Bland Altman plots (figure 6.2) and upper and lower limits calculation showed that the majority of scores were near to the mean for both pre and post-education conditions (1.96 SD range of the differences) and evenly distributed above and below the mean indicating no systemic bias. Both Bland-Altman plots revealed an agreement between non-specialist and specialist raters, however agreement pre-education was not as strong post-education. For comparisons of QASLS compound score pre and post-education (figures 6.3), the none specialist group demonstrated the greatest change in scores and alignment to the criterion rater. A Mann-Whitney U test was run to determine if there were differences in compound QASLS scores between non-specialist and specialist raters pre and post-education. Distributions of the compound score for none specialist and specialist raters were similar when assessed by visual inspection (figures 6.3). Median compound QASLS scores for non-specialist raters (7) and specialist raters (8) were significantly different pre-education ($p=0.038$) but were not significantly different (none specialist and specialist scores = 8, $p=0.218$) post-education. This suggests improved limits of agreement between raters regardless of experience following the education piece.

The 10 individual QASLS components demonstrated none to strong levels of agreement pre-education and weak to strong limits of agreement post-education in the non-specialist group, and weak to moderate limits of agreement pre-education and none to moderate limits of agreement post-education in the specialist group. Rating of pelvic tilt showed the strongest agreement post-education in both rater groups (Table 6.4). Within the non-specialist rater group, six of the ten components had a PEA% of 75% of higher, with hip adduction (94.1%), trunk (86.7%), pelvic drop (82.4%), noticeable knee valgus (82.4%) and touch down (82.4%) demonstrating the highest agreements post-education. Within the specialist rater group, the highest change in PEA% was seen in the arm (73.4%), pelvic drop (73.4%) and significant knee valgus (86.0%). Five out of ten components had a PEA of 70% or higher. Whilst the majority of Kendall's W values were weak, the corresponding PEA% were high for both rater groups.

Level of agreement between raters to a criterion score for QASLS compound score did improve post-education (Figure 6.4). This was also replicated for the component elements (table 6.5) where the level of agreement between raters and the criterion score demonstrated significant difference following the education piece for 8 of the 10 QASLS components. Average Spearman's correlations (R2) between all raters to the criterion rater are displayed in (table 6.5) with results implying weak to strong relationships. Whilst this suggests some potential continuing rater variability, overall following the educational piece the raters' compound QASLS scores and QASLS component scores (except knee valgus and wobble) demonstrated improved rater consistency to the criterion score (Table 6.5, figure 6.4).



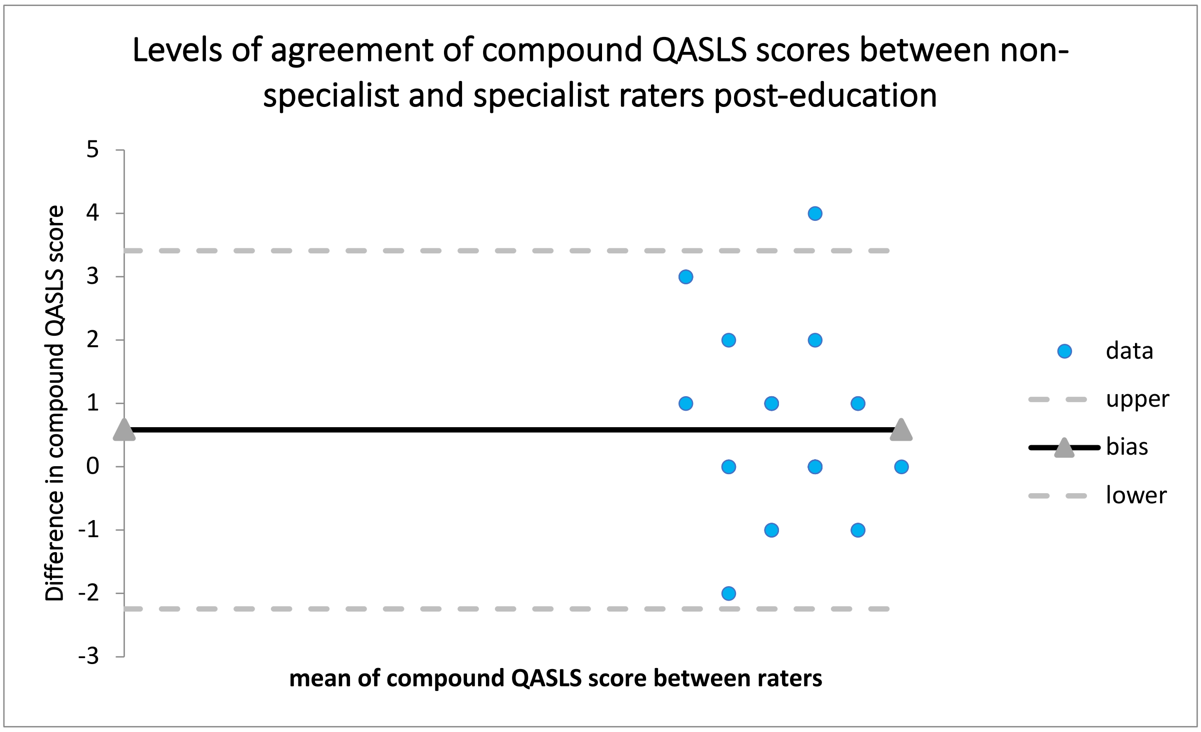


Figure 6.2 Bland Altman Plot of limits of agreement in compound QASLS scores between specialist and none specialist raters pre (Top) and post (bottom) educational intervention. The middle line represents the mean difference between the methods and the dashed line represents 95% limits of agreement.

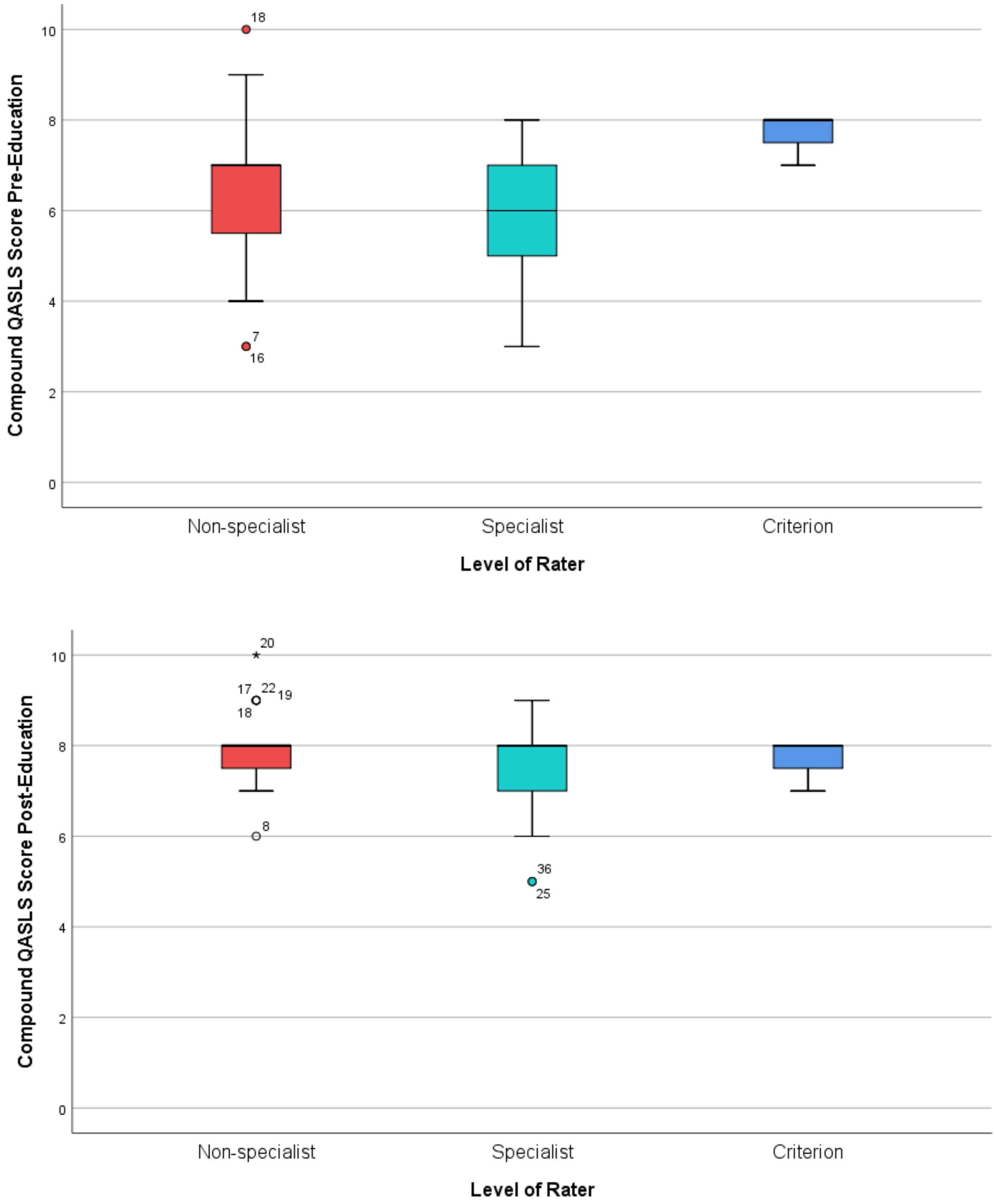
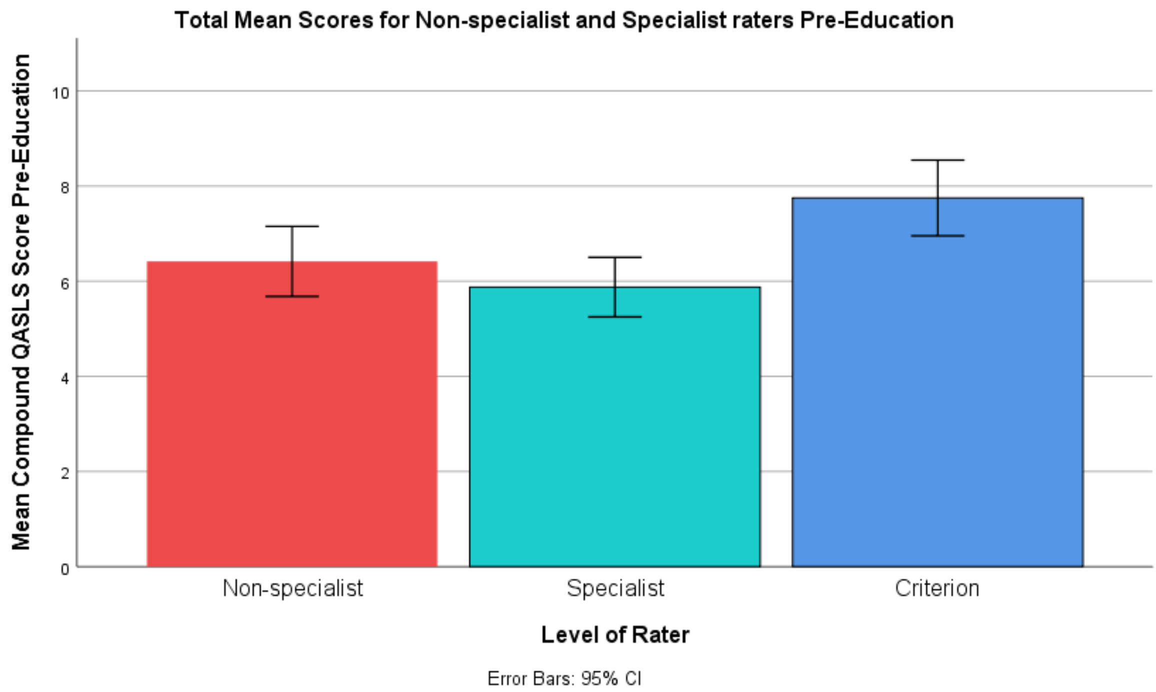


Figure 6.3 Compound QASLS scores of 4 athletes pre-education intervention (top) and post education intervention (bottom) by none specialist and specialist raters in relation to the criterion rater.

Table 6.4 Kendall's W, and PEA% for QASLS components pre and post educational intervention

	WHOLE GROUP				NON-SPECIALIST RATER				SPECIALIST RATER			
	Kendall's W		PEA%		Kendall's W		PEA%		Kendall's W		PEA%	
	Pre-Ed	Post-Ed	Pre-Ed	Post-Ed	Pre-Ed	Post-Ed	Pre-Ed	Post-Ed	Pre-Ed	Post-Ed	Pre-Ed	Post-Ed
ARM STRATEDGY	.367	.187	57.6	70.1	.273	.187	58.8	67.65	.462	.327	45.3	73.4
TRUNK ALIGNMENT	.205	.227	87.5	92.4	.250	.250	86.8	86.7	.200	.250	78.1	85.9
PELVIC HORIZONTAL PLANE	.315	.234	61.7	76.1	.286	.250	48.5	82.4	.375	.327	61.0	73.4
PELVIC TILT/ROTATION	.602	.607	56.1	54.9	.698	.653	42.7	42.7	.491	.576	54.7	56.3
HIP ADDN	.227	.291	84.1	65.6	.000	.173	94.1	75.0	.200	.375	53.1	53.2
NWB THIGH	.250	.171	63.6	68.6	.111	.278	61.8	64.7	.227	.091	56.2	59.4
NOTICABLE KV	.385	.218	67.4	88.3	.426	.250	66.2	82.4	.375	.250	56.3	86.0
SIGNIFICANT KV	.303	.163	75.0	55.8	.404	.159	75.0	39.2	.224	.187	64.0	68.6
TOUCH DOWN NWB FOOT	.289	.250	90.0	79.2	.250	.143	82.4	67.7	.327	.250	86.0	80.0
STANCE LEG WOBBLY	.302	.399	51.9	52.3	.167	.200	48.5	53.0	.400	.388	51.6	45.3

ADDN = Adduction, KV = knee valgus, NWB= none weight bearing, PEA% = percentage of exact agreement



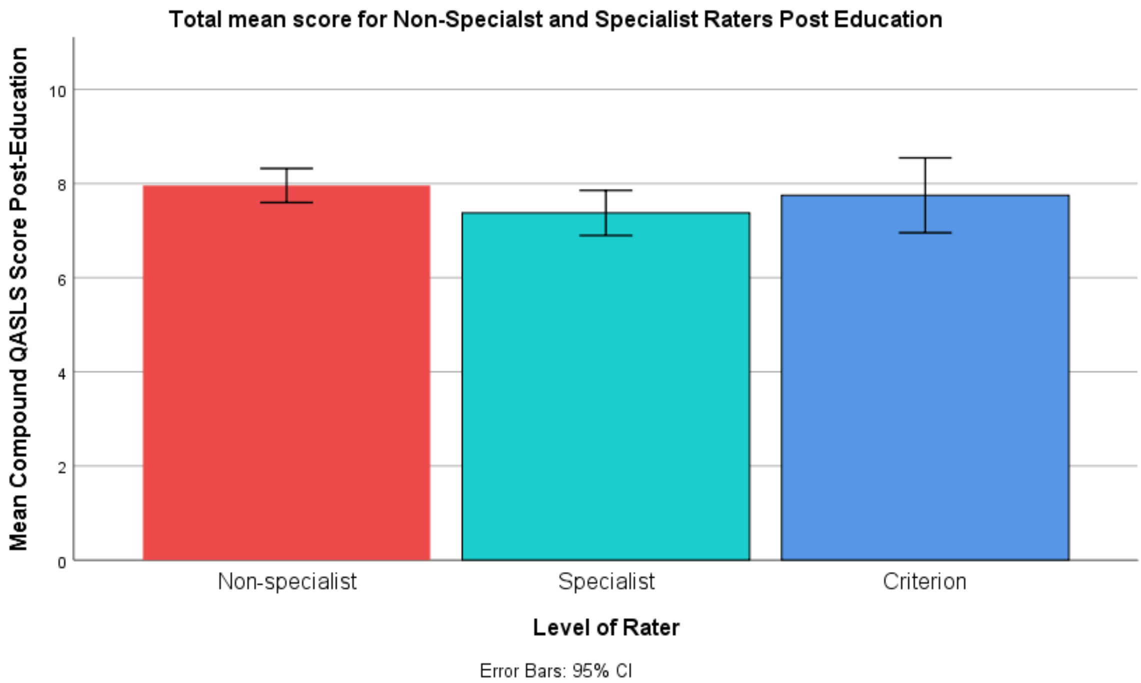


Figure 6.4 Total compound QASLS score for none-specialist, specialist and criterion rater and the standard deviation for each group.

Table 6.5 Rater Consistency between all raters and the criterion score

	Spearman's ® Between raters and Criterion Rater		% Raters Scores matching criterion score	
	Pre - Education	Post - Education	Pre - Education	Post - Education
ARM STRATEDGY	.460	.690	70.8	77.7*
TRUNK ALIGNMENT	-.370	.303	75.5	95.8*
PELVIC HORIZONTAL PLANE	.168	.920	68.7	85.4*
PELVIC TILT/ROTATION	.240	.640	52.0	66.6*
HIP ADDN	.149	.680	79.1	95.8*
NWB THIGH	.126	.240	66.6	79.1*
NOTICABLE KV	.110	.350	77.0	75.5
SIGNIFICANT DKV	.121	.930	33.3	52.0*
TOUCH DOWN NWB FOOT	.013	.259	85.4	95.8*
STANCE LEG WOBBLY	.093	**.292**	66.6	66.6

**P= <.001 for differences as assessed by Mann Whitney U. Values in bold denote significant difference P=>.05*

ADDN = Adduction, KV = Knee Valgus, DKV = Dynamic Knee Valgus, % = Percentage

6.4 Discussion

The main aims of this study where to examine the impact of an educational piece by determining levels of agreement between non-specialist and specialist raters pre and post-education intervention and to determine if the formal training improved rater consistency to a criterion rater.

Overall results indicate that completion of this formal educational piece improves levels of agreement within non-specialist and specialist raters for compound QASLS scores and some individual QASLS components. Whilst some variability does remain in scoring, especially within a specialist group, the aligning of raters from both specialist and non-specialist background to a criterion score did demonstrate significant changes post-education. This is an important delineation to make as just because raters demonstrate high levels of agreement does not mean that their decision is correct. In term of practical application, this study offers an important insight into the impact of rater training. It indicates that the completion of a specially designed 30-minute educational piece is useful for raters of varying experience and also for aligning compound scores and QASLS individual components scores to a criterion rater. This should impact overall inter-rater reliability and utility of the tool over multiple test sites and occasions. Currently, no other studies have examined levels of rater agreement or consistency for the QASLS tool directly, so a direct comparison to other work is not possible. Close examples within other qualitative field-based tools such as the LESS, TJA and FMS however maybe considered.

The majority of papers (Onate *et al.*, 2010; Padua *et al.*, 2011; Shultz *et al.*, 2013; Cuff, Palmer and Lindley, 2018) examine inter-rater reliability between raters of different experience rather than levels of agreement. Overall however high levels of rater reliability are seen in composite FMS (Leeder, Horsley and Herrington, 2016; Cuff, Palmer and Lindley, 2018), LESS (Padua *et al.*, 2009; Hanzlíková, Athens and Hébert-Losier, 2020) and TJA scoring (Onate *et al.*, 2010; Herrington, Myer and Munro, 2013). Reliability levels are usually reported as lower when considering individual components (or items that comprise the compound score), as was the observed case in this study.

6.4.1. Levels of rater agreement are impacted by an educational intervention, although this impact varies between compound and component scoring

Findings of this study suggest that levels of agreement of QASLS compound scoring between raters of varying level of speciality improved following an educational intervention. Whilst not totally comparable (as the researchers examined reliability not limits of agreement) the findings correspond with current research that has demonstrated excellent reliability (ICC= 0.82, 95%CI 0.41-0.93) in novice and expert raters following completion of a 2-hour training session in the use of the FMS tool (Cuff, Palmer and Lindley, 2018). Whilst the use of the compound scoring by raters receives criticism within the literature (Kazman *et al.*, 2014) on the grounds that it is not always clear what composite scores conclusively measure. Practically this demonstrates that an educational intervention positively impacts levels of agreement as seen through compound scoring.

Despite the impact on agreement around compound scoring, the individual components continued to demonstrate considerable variability amongst and between non-specialist and specialist raters. Whilst there was weak to moderate agreement noted for most components between rater groups, this was not always reflected within the percentage of exact agreement (PEA%). There appears to be commonality with this study and other research that examines the scoring of component items in other qualitative tools.

Previous research into the LESS has shown slightly higher agreement between a novice and an experienced rater when LESS components were assessed via kappa analysis and PEA% (Onate *et al.*, 2010), furthermore, Shultz et al., (2013) also concluded large variability between 6 raters in individual FMS component agreement as evaluated by Krippendorffs alpha ($\kappa\alpha$= 0.10-0.95).

Although both these studies select statistical methods to evaluate levels of agreement, they do so via different means which may account for the differences observed within the results. Krippendorffs alpha can be used for any data scale and multiple raters but calculates agreement via the differences observed within score ranges (Shultz, *et al.*, 2013) however kappa, especially unweighted treats all disagreement equally and is therefore not always appropriate for ordinal data (Sim and Wright, 2005). Similarly, Kappa cannot be run easily with multiple raters, whilst Fleiss Kappa is suggested for multiple raters it is best applied to ordinal categorical and nominal rating scales, as when applied to ordinal categories taken from continuous data (as is the case with qualitative compound scores) it can lead to loss of statistical power (Sim and Wright, 2005; Marasini, Quatto and Ripamonti, 2016). Kendall's W goes some way to eliminating the limitations around multiple raters and ordinal data by considering the level of agreement in data sets that cluster closer together in terms of score and rank. Levels of agreement designs that contain ordinal data with multiple raters are statistically difficult to analyse and whilst the use of multiple raters is important to clinical implications of findings, there remains a lack of research on the best methods for use on multiple raters and ordinal data (Sertdemir *et al.*, 2013; Leeder, Horsley and Herrington, 2016).

In relation to this study whilst the variability of rater agreement may be attributable to variability in rater scoring, it may also be attributed to unavoidable limitations within the statistical methodology. Therefore, the improvements noted in changes in the agreement between raters pre and post-education for the individual QASLS components should be interpreted with some caution.

6.4.2 An educational intervention does change limits of agreement between novice and expert raters but this is impacted by the level of rater experience

Multiple studies have analysed rater experience concerning qualitative measures (Ekegren *et al.*, 2009; Ageberg *et al.*, 2010; Onate *et al.*, 2010; Poulsen and James, 2011; Shultz *et al.*, 2013; Whatman, Hume and Hing, 2013; Tate *et al.*, 2015; Leeder, Horsley and Herrington, 2016), and although none of these works has compared relationships between pre and post educational intervention, many authors note discrepancies between novice and expert raters and continued varying scoring consistency.

When considering the average difference between QASLS compound scoring pre and post-education, on average post-education the non-specialist raters' scores changed by 1.6 and the specialist raters group changes by 1.7 compared to pre-education. Post-education the levels of agreement between raters speciality improved but this was more pronounced in the non-specialist group demonstrating higher levels of agreement. These results are partially supported by previous research, and whilst acknowledged reliability is not the same as levels of agreement, greater reliability has been shown in novice raters comparative to specialist counterparts.

When comparing untrained raters of differing clinical experience during FMS scoring high levels of reliability (ICC=0.906) and no significant difference between different clinical experience groups has been documented (Leeder, Horsley and Herrington, 2016) suggesting that less experienced clinicians performed equally as well as more experienced clinicians at FMS compound score rating. Officially, certified raters vs non-certified raters in the LESS tool have shown good levels of agreement (κ= 0.46-1.0) for LESS components to the extent that authors suggest qualitative measures can be used by clinicians of all levels of experience (Onate *et al.*, 2010). Furthermore, Shultz, et al., (2013) concluded that experienced raters demonstrated poor inter-rater reliability to raters with less than a year's experience who demonstrated fair reliability across compound and component FMS scores, which supports the premise of variety in qualitative scoring regardless of experience level. Although the previous authors have not provided a rationale for why scoring differs by rater experience, collectively theses papers illustrate that specialist experienced raters can exhibit lower levels of agreement than novice non-specialist raters and that education interventions are useful tools to closing the level of agreement gap between raters.

Following this educational intervention, whilst levels of agreement improved in both rater categories, the greater improvement is seen within the none specialist group may be due to differences in the clinical reasoning process of the none specialist and specialist raters, and whilst beyond the scope of this study, additional investigation around the rationale underpinning the decision-making process of raters may also enhance the evidence base for the educational training around the QASLS tool. In the studies of Albarqouni *et al.*, (2018) and Case, Harrison and Roskell, (2000) several differences within the clinical reasoning process of novice and expert clinical groups have been identified. Less specialist novice raters have demonstrated less refined retrieval and storage of knowledge than expert groups (Case, Harrison and Roskell, 2000). When partaking in evidence-based practise educational interventions, this group of practitioners are more likely to focus on acquiring and appraising evidence, frequently at the expense of applying and assessing new information into clinical practice (Albarqouni *et al.*, 2018).

This lends support to the smaller increase in levels of agreement seen in the specialist rater group post-education intervention in this study and may explain the variation seen in rater scoring. Due to more refined clinical judgement and problem-solving ability, specialist raters are better able to transfer prior knowledge into clinical practice. Whilst a specialist rater may be aware of a component strategy within the compound score, depending on the raters clinical or sporting speciality they may not deem the strategy detrimental or essential to performance and therefore the component strategy may not get recorded, which could ultimately impact overall compound score.

Whilst levels of agreement around the use and application of a new clinical tool are undoubtedly important to the widespread application of its use, it is argued that the interpretation of the outcomes of the tool especially by expert specialist raters is less so. In comparison to non-specialist novice raters, “expert specialist” knowledge is defined by networks of knowledge that impact clinical decision making (Wainwright *et al.*, 2011) and are in essence what characterise experts as experts. The specialist raters in this study had on average an extra 6 years of clinical experience comparative to the none specialist group, with some specialising in set sports and some set anatomical regions. Therefore, unreasonable to expect lower levels of agreement between specialists as it is that level of disagreement that delineates them as specialists, and therefore 100% agreement between specialist raters from differing sporting backgrounds might be considered a negative finding. This assumption agrees with studies that have demonstrated differences in the thought processes and transferring of new knowledge through meaningful learning in novice and expert raters (Case, Harrison and Roskell, 2000; Wainwright *et al.*, 2011; Montpetit-Tourangeau *et al.*, 2017; Albarqouni *et al.*, 2018). It is suggested that following educational intervention of a qualitative assessment tool, changes in limits of agreement between specialist raters are expected, but due to potential differences in clinical reasoning ability, the impact of an educational piece is likely to result in smaller changes in a specialist rater group. This study recommends the use of an education session such as the one used within this study to both specialist and none specialist raters to strengthen the utility and clinical application of the QASLS tool before application by practitioners.

6.4.3. An educational intervention did improve rater consistency to a criterion score

An additional aim of this study was to determine if the completion of an education piece improved further alignment of rater scoring to that of a criterion rater. Following one education session consisting of 30 minutes of online training, both non-specialist and specialist raters demonstrated greater consistency to independent components of the QASLS score and total compound QASLS score with the criterion score. As previously discussed levels of agreement between raters (especially around the application of a tool) are important, however strong rater agreement is not the same as correct agreement, and therefore validation to a criterion rater is an important finding which should lead to higher levels of agreement and greater application to improving the credibility of QASLS results. There is a paucity of information in relation to the examination of educational interventions on levels of agreement and scoring consistency in qualitative measurement tools.

When considering the percentage of rater scoring to a Criterion score pre and post-education (table 6.5) eight out of ten QASLS components improved significantly (P <0.05) with an average improvement of 14% to the criterion sore and those eight components increasing to over 65% agreement to the criterion. Post-education, the trunk component was the greatest to improve (20.3%) in agreement towards the criterion score, whilst this component is easy to observe from the frontal and sagittal plane, trunk lean can occur towards and away from the midline (Dingenen, Staes, *et al.*, 2018), which might not have been as easily classifiable by a rater. It is possible that the additional information and video examples provided in the educational piece, raters were more readably able to identify trunk lean in either direction which attributed to the improved scoring.

Improved identification of trunk lean by raters is a valuable outcome of this study, due to its known associations to lower limb injury risk factors, better identification of trunk strategies by practitioners (especially in addition to other lower limb components such as hip adduction and dynamic knee valgus) may lead to improved identification of risk factors which may impact overall lower limb risk mitigation. Only two items within the QASLS components (Knee valgus beyond 2nd toe and stance leg wobble) did not demonstrate improvements to a criterion rater. This finding is not surprising as previously documented in Chapter Two, knee valgus is the most documented and explored movement strategy within the literature and during a clinician's formal education. It is, therefore, the most likely QASLS component that both none specialist and specialist raters are likely to be familiar with. This movement may subsequently be the hardest component to influence by educational pieces, due to the extend and current ongoing knowledge potentially held by raters.

6.5 Strengths and Limitations

This study has contributed to the qualitative movement assessment literature by further analysing the effects of a 30-minute online educational piece on levels of rater agreement but also the consistency of that agreement to a criterion score, in an attempt to move beyond the measure of reliability that prevails in the current literature. Where previous papers have limited rater numbers to 2-3, to improve the clinical findings and application of the QASLS tool across multiple raters – which is essential to larger participants number studies – a larger number of 12 raters were selected. Whilst methodology was carefully selected to include statistical tests that are more robust at handling multiple raters and ordinal data, it is acknowledged that statistical analysis of QASLS components has been difficult. However, despite this, results have demonstrated changes in levels of agreement and consistency especially when analysing compound scores.

Another limitation of the study is that raters were selected from the same sports institute, and whilst each rater had varying levels of experience in terms of clinical background, variety of sporting background, previous exposure to the QASLS tool and varying levels of formal educational status that are arguably representative of the wider clinical profession, all raters had been qualified for a minimum of six years and it is, therefore, unknown if these results may be applied to newly qualified or student level practitioners. Consequently, it is suggested that clinicians working with these populations may wish to run the educational intervention within their own populations to ascertain levels of agreement pre and post-education (Shultz, *et al.*, 2013).

Finally, whilst testing sessions were completed three weeks apart and a video order re-randomised which served as a strength of the study to reduce any potential recall bias of participants by raters, re-evaluation of the impact of the educational piece was completed on the same day as the training session. Therefore, the long-term impact of the limits of agreement and subsequent long-term knowledge acquisition between rater groups and to the criterion score remains unknown. Meaningful learning implies that knowledge gained by learners makes sense in their future practice (Montpetit-Tourangeau *et al.*, 2017), and whilst this study is believed to be the first to examine limits of agreement and consistency of QASLS scoring pre and post-education intervention, further research is warranted in both none specialist and specialist groups to fully establish the learning impact of regular use of the QASLS tool comparative to none regular use, to further understand how new rater knowledge is transferred to solve movement quality-related new problems.

6.6 Conclusion and Practical Applications

The completion of a short 30-minute online education piece meaningfully improved the limits of agreement of compound QASLS scores and QASLS component scores between non-specialist and specialist raters, as well as overall rater consistency to a criterion rater. These findings confirm the potential of an educational piece to improve the application of the QASLS tool in wider clinical practice. Clinicians should expect changes in non-specialist and specialist raters, although it is to be expected that these changes are likely to be smaller in specialist groups due to potential clinical reasoning differences evidenced in raters with differing degrees of speciality. Some variation in scoring regardless of rater experience, especially in QASLS component scoring. Whilst raters may agree on identifying individual strategies the perceived impact of the outcome by specialist raters may result in none recording of an individual component which may impact total compound QASLS score. Whilst significant changes to alignment to a criterion score were also noted, the longitudinal carryover of this knowledge remains unknown and therefore caution is advised. Clinicians are encouraged to consider regular re-training of all rater levels until the longer-term learning effects have been established by future research.

Overall the QASLS system is a useful movement assessment tool and the addition of a short rater training piece can be effectively utilised across multiple raters in an easy straightforward way that should impact inter-rater reliability across multiple raters, test sites and test occasions. This is key to any movement assessment tool being universally adopted into mass profiling successfully.

Chapter Seven

7.0 Conclusions and recommendations for future work

7.1 Summary of Thesis

The thesis delivered new information regarding a clinically feasible profiling tool and its subsequent use in youth athletes, to gauge potential future impact on the ever-escalating injury burden and injury incidence. This was achieved through pilot work exploring the clinical utility of current motion analysis methods, tools and tasks, and the development of a qualitative methodology. It then became important to discover and identify the impacts on the adolescent athlete, through investigation of the growth and maturational process over the course of a competitive season and academic year, to assess the ability of the tool to provide pertinent information. To further advance widespread application of the tool which is a requirement of effective practice and intervention, the final study aimed to investigate and improve the application of the tool through the development of an educational piece to better enrich rater-training.

Finally, this current chapter will provide a summary of the key findings of this work, reviewing the aims and findings of previous chapters and the clinical and potential academic implication for the research. This is supported by additional discussion of the limitations encountered, and on overall concluding statement, before final recommendations for future research around injury risk and its mitigation in the adolescent population.

7.2 Discussion of aims, practical implications and limitations

Following an extensive review of the literature, it became clear that the current understanding of the scientific sports medicine community regarding injury prevention did not match the latest frameworks and models used to identify risk of and predisposition to injury. Prematurely, the research literature would appear to have collectively insinuated sports science and medicine understood injury prevention and injury risk mitigation, before it actually did.

Sports injury prevention is a complex phenomenon. As such finding a singular solution to a multifaceted problem was looking highly unlikely, and reflected the wider issue of reductionism to singular parameters in the current assessment and intervention strategy approach. It was identified that the latest injury prevention models do not align to current injury prevention assessment and injury intervention processes, here the former proposes multiple interacting factors in injury causation, whilst the later looks for an attempt to intervene often with a single factor. With clear gaps in literature pertaining to the interactions profiling tools and interventions and the context into which they are applied. It was acknowledged that for the injury prevention problem to be revisited, a complex systems approach was required to accommodate the multifactorial and ever-changing nature of sports injuries. Following the reasoning of a complex systems approach, by recognising complexity and context from the beginning of a sports injury process, practitioners will obtain better clinical judgements and directions of travel for those involved in the injury process.

It appeared the majority of injury prevention processes, research and comprehension was born from laboratory based quantitive methodologies, which, though being shown to be highly valid and reliable, do not provide a full clinical picture of an athlete's movement, providing a static reference point along what is a very dynamic fluctuation continuum. With the potential limitations around ability to interpret the inherent and essential variability contained within human movement, combined with the practical limitations of widespread clinical utility, the exploration of alternative human movement analysis was justified.

Qualitative visual assessment was identified as an emergent method of analysis of movement quality, which appeared to better represent the shift away from isolated muscle and joint testing, towards an integrated whole movement pattern approach. In addition, the qualitative approach offered an option to address the issues around the contextual processes of injury, not widely implemented through the quantitative process, which could impact the wider implementation problem of transferring research evidence into clinical practise.

For a qualitative method, such as the QASLS tool to have meaningful real-world application, establishing of the reliability, validity and associated measurement error of the tool was an important start point. In addition, it was also important to understand if the tool could capture multiple aspects of movement quality simultaneously, to further add to the research base by providing a means to capture variability. Furthermore, the application in different populations, such as an adolescent group, was also identified as an important factor to understand the external validity of the method in preparation for prospective study. When dealing with an adolescent group, a longitudinal multi-point assessment approach was recognised as a helpful addition to broaden cross-sectionally established knowledge, by further evaluating the effects of growth and maturation to deepen the insight of the contextual applications of a qualitative assessment tool within this specific population. Finally, in order for widespread use of the tool by practitioners in the field, to allow the multicentre use required for a prospective study, inter-rater training appeared to be a key requirement, an educational piece was therefore needed to explore further gaps in the research beyond rater expertise, to how raters can be appropriately trained.

A discussion for the practical implications and limitations encountered in this research which relate to the original research objectives are included below.

The first aim of the thesis was to investigate the intra-rater, inter-rater, within and between session reliability and associated measurement error of the 2D parameters during the single-leg squat and single-leg land. This was to allow for the subsequent development of validity, reliability and associated measurement error of the qualitative tool during the unilateral loading tasks. As identified by the literature review in chapter 2, despite the frequency of reported research into 2D parameters regarding the knee, there was a distinct absence of data evaluating the trunk and upper limb and the subsequent impact on the lower limb (Williams *et al.*, 2017; De Blaiser *et al.*, 2018; Dingenen, Staes, *et al.*, 2018). Chapter 3 investigated rater and sessional reliability of 9 different 2D parameters incorporating 5 different body segments from 2 movement planes. This approach is believed to be the first to evaluate more than 3 parameters within the same movement pattern. As such this had added to the research by emphasising multiple aspects of movement quality in a more multi-dimensional way.

With regards to the development of validity of the QASLS tool relationships between QASLS components and 2D measurements were analysed. Results showed statistically significant correlations for all components during the unilateral squat task, and for trunk, hip and knee components during the landing task. This is an important addition to movement quality research, as the visual observation tool has been shown to correlate to multiple 2D variables (trunk lean, hip, knee valgus) that have previously demonstrated as contributors to injury (Willson and Davis, 2008; Mann *et al.*, 2013; Dingenen *et al.*, 2014; Myer, Ford, *et al.*, 2015; Tamura *et al.*, 2017; Gwynne and Curran, 2018; Plummer *et al.*, 2018).

Generally, the within and between session reliability of the 2D kinematic parameters was moderate to excellent for both limbs across unilateral squatting (ICC=0.67-0.98) and landing (ICC=0.66-0.98) tasks. Whilst all SEM values were less than SDD values during both tasks, when expressed as % of SDD and reported alongside CV%, overall task variability and movement pattern variation was high. This was a key finding of the methodology as the variability of movement evidenced within the 2D parameters, suggests that each movement is highly individualistic and no one person is likely to replicate the same movement in the same way. As such it also means that too few participants select the same pattern for a mean to be significantly recognisable as a true representation.

This led to the major finding of this chapter which was the unexpected reframing of the statistical process, and new statistical learnings regarding the analysis of the data. The determining of inter-rater reliability is readily acknowledged in the literature as a difficult process (Morris *et al.*, 2008; Koo and Li, 2016). Whilst the recommended statistical methods of Cohens kappa and percentage of exact agreement (PEA) (Morris *et al.*, 2008; McHugh, 2012; Hernaez, 2015) were selected, neither method was without fault, and neither method appeared to solve the establishment of inter-rater reliability in a straight forward way. This finding was likely due to the “base-rate problem” inherent within the kappa statistic (Morris *et al.*, 2008). In data sets where participants frequently change their rank order but also cluster together, like the participants in this study, a kappa in unable to establish true prevalence in highly homogenous populations. Whilst it is judicious to acknowledge the limitation of non-heterogeneous cohorts on the kappa method. It is arguably more pragmatic to acknowledge that truly heterogeneous participant samples are highly unlikely in elite sport. This is an important finding as it further accentuates the void between the application of research and practical clinical application, that was previously exposed within the literature review. By demonstrating the parallax of data smoothing that results in the masking of performance, this finding further imposes upon the profession the requirement for a rethink around the statistical modelling required. Especially if the goals of research are to remain paramount to performance, reliability and impactful real-world meaning.

Whilst the level of rater training was initially a limitation within chapter 3, it became a significant point of interest and the final learning point that became the foundation of chapter 6. Within the literature review, rater-training emerged as a key component to robust inter-rater reliability (Padua *et al.*, 2009; Minick *et al.*, 2010; Crossley *et al.*, 2011; Shultz, Scott C. Anderson, *et al.*, 2013). Though level of expertise appeared to be influenced by rater-training (Chmielewski *et al.*, 2007; Minick *et al.*, 2010) there appeared to be no research regarding methods of training practitioners. Chapter six provided information regarding the impact of an online-learning piece on levels of rater agreement. This improvement of levels of agreement and agreement to a criterion rater was of particular interest, as it demonstrated an impact on the quality of data that could be inputted into the QASLS tool. Good data improves internal validity which positively impacts the improvement of reliability. This new information regarding delivery of rater-training has strongly added to the first and fourth research aims and further developed the research base. By offering a viable way of improving rater-training, this in turn improves reliability, which allows the engagement with prospective research and the subsequent evaluation of intervention-based approaches.

Following the establishment of the methodology, and the validity and reliability of the QASLS tool. Chapter four aimed to address the second and third aims of the thesis and establish what factors impacted the application of 2D and qualitative movement assessment to both unilateral tasks in an adolescent population. In keeping with the complex systems approach, this was to inform practitioners and the knowledge base around the context (in this instance adolescence) the qualitative tool would be required to operate within. The 2D variables demonstrated as reliable within chapter three where applied through chapter four to investigate the consistency of unilateral task performance as evaluated by 2D kinematic variables and QASLS score.

Large variation was present in each parameter across both tasks and PHV groups, moderate to poor ICC's and large CV% throughout this population group, may suggest that an adolescent's individual movement pattern cannot be defined by one variable and will be driven by numerous factors. Calculation methods of QASLS scoring demonstrated significant differences in task performance between PHV-groups, which maybe suggestive of NMC induced changes in movement patterns during growth. Collectively, the data sets from chapter four suggests that maturational effects are present. This tentatively supports the application of growth and maturational factors alongside the application of movement quality assessment tools with an adolescent population and may further assist understanding with future prospective studies evaluating injury risk.

Further important findings of chapter four, were that performance scores represented by a mean, washed out performance bandwidth of an individual as low and high scores became negated (Cormack *et al.*, 2008). Whilst a bandwidth of performance was not surprising given the non-linearity of biological movement processes, the potential impacts regarding its diminishment was. This information adds a further dynamic of consideration to the movement quality literature and the thesis first and second aims, by further highlighting the different performance outcomes the same factors and mechanisms have on different athletes. As well as the continual evolution and adaption of the bodies sub-systems. This has additional implications for the external validity of the QASLS assessment tool, as it proposes an alternative approach to a global view of risk with ever emergent properties. With better understanding of risk factors, practitioners can play a better role regarding injury prevention and risk mitigation.

Although common in current methodological design (Barker-Davies et al., 2018) the cross-sectional research design employed in chapter four, limited further generalisations of the results over greater periods of time. The rate of change of unilateral task performance might have occurred differently than that observed at the time of testing. Retrospective consideration of this limitation was used to inform the methodological constructs of chapter five, helping to inform the third aim, and addressing the previously identified literature gaps of minimal longitudinal data sets and reporting around seasonal variation.

The findings of chapter five demonstrated linear decreases of QASLS compound scores during unilateral task performance towards advancing maturation. Interestingly, whilst significant differences were noted during single-leg landing over the course of a season, this significance was not demonstrated during single-leg squat regardless of maturational status. Although the impact of the observed changes as measured by compound score during squatting may not be meaningful, changes in landing were observed that might impact injury risk or have training implications. Measurements of QASLS components displayed with ankle, balance and upper limb strategies were associated with unilateral task performance in pre or circa-PHV athletes or those at earlier PAH%. Knee and trunk component use also declined with advancing maturation, which may be reflective of the different maturational stages of body segment development encountered during growth (Quatman-Yates *et al.*, 2012; Difiori *et al.*, 2014; Cumming *et al.*, 2017). The collective data of chapter four and chapter five suggests that maturation effects impact the neuromuscular performance of two unilateral tasks and that landing patterns will remain highly variable but change during the course of a season. In addition, different body segments will be affected at different stages of maturation during both tasks, which may be inciteful to practitioners in the development of rehabilitation programmes and movement assessments throughout an adolescent athletes' development.

Whilst the finding is original and adds both to the MSK profiling and adolescent literature, it is important to acknowledge the contextual boundaries and caveats of application of this research piece. The selected unilateral tasks have been described as injurious movement patterns in both the adult (Edmondston *et al.*, 2013; Maclachlan, White and Reid, 2015; Raïsänen *et al.*, 2016; Bennett *et al.*, 2017) and adolescent literature (Rejeb *et al.*, 2017; Von Rosen, Kottorp, *et al.*, 2018). However, the methodology of chapters three-five of this thesis was designed for a clinical assessment scenario, and as such, the closed skill environment of testing may not be fully reflective of a competitive training or competition environment. Although this restricts the current results to a clinical scenario. In terms of movement skill assessment, this context is the first on a movement skill development paradigm (Quatman-Yates *et al.*, 2012; Wild, Munro and Steele, 2015; Rexen *et al.*, 2016; Agresta *et al.*, 2017), and whilst future research into open skill contexts that would likely impact the complexity of the tasks would be beneficial, the current closed skill context is considered the most appropriate for use.

The main finding of chapter six has been developed within the background of the thesis first aim and chapter three, however, due to the importance of inter-rater reliability to multicentre use to recruit the participant numbers required for a prospective study, the final thesis aim and premise was to identify the effect of an educational piece on consistency and levels of rater agreement. Additional findings of chapter six, offer a revisited approach to inter-rater reliability by providing an example of a rater training tool for qualitative assessment. The comparison of rater scoring to a criterion measure offers a different perspective to rater-reliability that is not commonplace within the current literature. Comparison to a criterion specifically targets subjectively of a rater and offers an alternative approach to accommodate the complex nature of rater-subjectivity, rather than over operationalise and streamline a naturally rapidly evolving process.

7.3 Summary of main learnings in relation to thesis aims and objectives

The initial aim of the thesis was to improve the field of musculoskeletal profiling by establishing the validity and reliability of the new qualitative "QASLS" MSK profiling tool, due to historical limitations in current philosophies regarding injury screening, profiling and singular solution injury prevention research. Following scrutiny of the literature into a critical overview, it became apparent that any future approaches to the problem were viable across a complex and continually evolving context, and that one of those potential drivers of complexity was adolescent youth development. Profiling tools and movement tasks that specifically mitigated to evaluate the impacts of maturation were relatively unexplored. Therefore, the thesis evolved towards the specific aim of deepening understanding of how movement quality changes during growth and maturation, to not only improve profiling generally but to improve current understanding of its application into a complex population.

Key learnings by objective

1) ***To develop valid and reliable methods, and associated measurement error for 2D kinematic and qualitative movement assessment tool, during two unilateral limb loading patterns***

- 2D kinematic variables from both the frontal and sagittal planes can be measured with moderate to excellent within and between session reliability and intra and inter-rater reliability during unilateral landing and squatting tasks

- This did not extend fully to the upper limb measurements due to the size of SDD change, but it is one of the first studies to attempt UL analysis within a whole movement pattern. Further substantiation of the UL for both tasks is required but is currently limited by lack of UL research generally across the biomechanical literature

- SEM values and SDD values were acceptable during both tasks, however when expressed as %SDD and reported alongside CV%, task variability and movement variation was high, suggesting movement is highly individualistic

- Too few participants select the same movement pattern for a mean to be significantly recognisable as a true representation of movement

- The QASLS tool has demonstrated moderate to excellent within and between session reliability and intra-rater reliability, and is a viable, accessible, portable method of analysing movement quality of unilateral tasks in the practical setting

- Significant relationships were observed between trunk, hip and knee QASLS scores and 2D kinematic variables from frontal and sagittal planes during both unilateral loading tasks

- Current statistical modelling is identified as a potential barrier to profiling research as the parallax of data smoothing can result in whitewashing of performance which has potential impacts on exacerbating the current void between the construction or research protocols and practical real-world application

2) ***To establish what factors, impact the application of 2D and qualitative assessment in the youth adolescent population during unilateral loading tasks***

- There are associations between maturity status and movement quality of adolescents during both unilateral tasks and both 2D and kinematic qualitative QASLS variables. Therefore, inclusion of maturational measurement alongside profiling tools when applied to an adolescent population should be considered to ensure results are interpreted with correct inference

- Participants that classified as prepubertal exhibited less consistency in frontal plane hip and knee variables, but greater consistency in frontal and sagittal trunk variables than those that classified within growth spurt during both unilateral tasks

- SLL performance significantly improved with age, with pre-PHV athletes requiring more movement strategies than the circa-PHV group to complete the same task. Practitioners should be mindful that compound QASLS scores maybe higher in prepubertal athletes but that is relative to phase of growth and not necessarily indicative of an intervention requirement

- As with adult participants in chapter 3, large variations of movement during each 2D and qualitative variable was present across all PHV groups. The large performance variations are potentially indicative of the effect of maturation status on task performance within an adolescent setting

- The data set indicated limitations of whole movement pattern evaluation of individual 2D variables, as singular variable appears to only represent a segment of a total movement picture. This is similar to the reductionist limitations also observed in adult participants

- When considering calculation methods of QASLS scoring in a youth population, the highest score method displayed statistically significant differences in performance between PHV groups, that were not evident when the mean of 5 repetitions was reported

- When average scores of multiple repetitions are collated, high and low scores (or more or less strategies) become less prominent which diminishes insight into an individual's movement bandwidth. This has important implications for the adolescent population which might be undergoing a natural change in their performance of movement bandwidth

- In the context of a youth population CV% of 2D and QASLS variables were persistently above proposed 10% CV limits (Cormack *et al.*, 2008). It is likely that CV% variables below 10% do not adequately represent the performance variability within a youth population, and practitioners who choose to use CV% to denote adolescent human performance variability not methodological variability, may wish to adjust acceptable CV% to higher levels

- Practitioners should use the highest score method when using the QASLS tool on an adolescent population to negate the possibilities of capturing an atypical performance of unilateral loading tasks

3) ***To establish if performances of the unilateral loading tasks change over a competitive season or training period***

- Seasonal change in unilateral loading tasks did occur but this was limited to circa and post-PHV groups during landing only. Performance of SLL task changed between the start to mid and mid to end phases of testing for those around the growth spurt at 85-95 PAH%, and start to end phase differences were noted in those >96-100 PAH%

- Performance of either unilateral loading task did not change over the course of a season for prepubertal athletes. This poses important questions regarding the role of profiling in this group and practitioners should be mindful that movement variability at this stage of growth maybe too large to track and draw consistent meaningful conclusions from

- SLS performance did not appear to change over the course of a year which is in contract to the cross-sectional data and previous general assumptions held within the literature that squat performance changes are the norm

- Unilateral landing performance may therefore be a better measure for practitioners looking to track adolescent movement quality over the course of a year. Whilst SLS appears to provide useful insight into the selection of strategies by individuals for task completion, and impact of maturation on individual performance at the cross-sectional level, squat performance changes do not seem to appear at longitudinal evaluation

- Longitudinal profiling in adolescents that are potentially in a growth spurt phase should therefore be completed at multiple points of the year, rather than stand-alone sessions at the start of a pre-season or the end of an academic year

- There was no significant interaction between sex and unilateral task performance as assessed by compound QASLS score in this study. However due to COVID-19 this may be impacted by the number of participants that were able to complete the study, future research should continue to evaluate this in larger participant groups

- QASLS component selection to complete either unilateral task is affected by PAH%

- Use of ankle and maintenance of unilateral stance (such as arm or touch down strategies) appear to occur more frequently at an earlier PAH%

- Use of a knee strategy was present in most participants that classified in 85-96% of predicted adult stature, the band most associated with rapid growth

- Trunk strategies appear to be present throughout the growth and maturation process, there is observed trend of declined use towards advancing maturation, although half of participants still required its use during squatting (44-57%) and landing (60-68%)

4) To establish the effect of an educational piece on levels of rater agreement and consistency of rater methods

- A 30 minute educational piece significantly improved meaningful levels of rater agreement and alignment of agreement to a criterion rater, although this impact varied between compound and component scoring

- On-line learning is an appropriate tool for rater-training to improve agreement in specialist and none-specialist raters of the QASLS profiling tool

- When selecting statistical methods to evaluate limits of agreement in qualitative movement quality tools, that investigate ordinal categories taken from continuous data, unavoidable limitations within most recognised statistical methods remain. Kendall's W goes someway to eliminating these limitations and is a recommended route for future research methodological considerations

- The findings of this thesis are the first to demonstrate the potential of an educational piece on improved agreement between raters and to a criterion rater. However, results were only collected in the short-term. The long-term impact of rater knowledge acquisition and application therefore remains unknown and is a direction for future research

7.4 Conclusions

The work of this thesis has contributed to new knowledge regarding the development of musculoskeletal profiling and specific aspects of consideration for application within an adolescent population. During the course of this work, reliable and valid methods of use of a qualitative visual assessment tool have been developed and correlated to 2D variables associated with injury risk in both the adult and adolescent population. Due to the complexity of sports injury, the thesis offered a different approach prior to the commencement of any prospective research, by acknowledging the latest injury prevention frameworks and starting with context and variability, rather than starting with set solutions for set pathologies. Accepting complexity and the innate variability of human movement demands changes in the construction of our evidence base, movement assessment processes and injury intervention strategies.

The consideration of the qualitative approach has allowed a non-linear path to be explored that offers a new outlook for the prospective movement assessment research, that strive to understand multiple evolving parameters and the gaining of a deeper understanding that can better guide the rehabilitation process and the occurrence of injuries in real-life practise. The continual consideration of context has allowed exploration of the tool in an adolescent cohort, with the added consideration of maturation. Allowing for exploration of interactions between adolescents, movement quality assessment and seasonal performance, has provided potential insight into additional considerations for future practitioners working with this cohort. The further results of the educational piece further support the use of the qualitative method by opening up its use in multi-centre studies becoming a viable choice in additional prospective studies by those wishing to pursue this topic of research.

Cumulatively, the contents and approaches explored in this thesis have provided additional information regarding the improvement of inter-rater reliability, methodological approach of qualitative visual rating criteria, and considerations around the context of growth and maturation processes encountered when using an adolescent cohort. Thus, providing a real-world example for future research to follow, moving the research base closer to meaningful, clinically applicable prospective studies, that deepen the understanding of profiling and its potential role in injury prevention and risk mitigation.

7.5 Directions for future research

The natural progression of this research would be to a prospective study and potential intervention work. There are multiple possible avenues of development for future work, following the learnings of this thesis recommended approaches would be, to start with and continually evaluate the context of the injury, the athlete it is occurring too, and the environment in which it is occurring. This will inform and provide movement assessment tools that can keep up with the natural rate of change of human movement, and the rate of change of a performance environment. Based on the suppositions of the complex systems approach (Bittencourt *et al.*, 2016), and the data sets from chapters three-six future prospective work should further assess relationships between NMC, performance of unilateral tasks and different contexts. Studies examining participant performance under fatigue (both physiological and cognitive), in more complex open skill environments, and at different points of a hormonal cycle, are all examples that might provide different information on how an athlete's context impacts a current injury problem.

Additionally, further research into more longitudinal measures of the chosen contexts over a season, multiple seasons or school years in an adolescent group, would expand the knowledge base on normative levels of movement variability to establish if there are points across a year or a career that may be associated with changing levels of injury risk. Prospective work could also look to advance rater-training, to increase multi-centre testing and the possibility of larger participant numbers to further quantify injury as a problem. Following on from contextually explorative larger prospective studies, will be better intervention studies. This could further provide better contextually driven prevention strategies or solutions, that are more meaningfully impactful on the overall complex injury problem.

Chapter Eight

8.0 Supplementary Pilot Work

In the development of the methodology – limitations in previous work negating the inclusion of trunk and upper limb were identified. Given the importance of trunk position to Lower Limb injury, its inclusion in any video capture is highly important and extensive methodological piloting was required.

Supplementary A: Camera Set-Up Positioning

Previous research (Table S1) has reported camera distances of 2.9m-10m from participants to capture lower limb movement. The majority of the studies reviewed compare 2D parameters with 3D, with all previous research papers reporting testing occurring within the laboratory-based environment. Laboratory-based settings are generally large in area size, with square footage that is unrepresentative of the working world. Many treatment and clinical spaces are equivocal or smaller than some of the reported distances for 2D capture camera set-up (e.g. 4.5m x 4.5m). To overcome some of the previously reported 2D and 3D assessment limitations regarding portability and feasibility, to improve clinical utility and encourage extensive usage of the 2D variables and QASLS methodology, camera set up had to be reconsidered for this research.

Table S1 – Examples of camera set-up for 2D data capture

Authors	**Movement Assessment Task**	**Camera Distance**	**Camera Height**	**Movement Plane Captured**	**Body Segment Captured**
Barker-Davies (2018)	SLS	4.8m F, 3.6m S	0.77m both planes	Frontal & Sagittal	LL
Dingenen (2014)	SLS	3.5m	0.6m	Frontal	Trunk & LL
Edmondston (2013)	SLS	2.5m	Participants ASIS	Frontal	Trunk
Herrington (2017)	SLS	10m	0.6m	Frontal	LL
Horan (2014)	SLS	3m	1m	Frontal	LL
Poulson (2010)	SLS	4.5m	Unknown	Frontal	LL
Räisänen (2016)	SLS	4.5m	Unknown	Frontal	LL
Schurr (2017)	SLS	2.4m	1.2m	Frontal & Sagittal	Trunk & LL
Tate (2015)	SLS	2m	1m	Frontal	LL
Weeks (2012)	SLS	3m	1m	Frontal	LL
Munro (2010)	SLS & SLL	10m	0.6m	Frontal	LL
Munro (2017)	SLS & SLL	3m	0.5m	Frontal	LL
Miller (2009)	SLS & VDJ	2.9m	0.58m	Frontal & Sagittal	LL
Burnham (2016)	SLSD	3.5m	0.3m	Frontal	Trunk & LL
Dingenen (2015)	SLVDJ	3.5m	0.6m	Frontal & Sagittal	Trunk & LL
Holden (2015)	DVJ	Unknown	1.03m	Frontal	LL
Fort-Vanmeerhaeghe (2017)	TJA	3m	Participants Waist	Frontal & Sagittal	Whole
Lininger (2017)	TJA	Unknown	Unknown	Frontal & Sagittal	Whole
Read (2016)	TJA	5m	0.7m	Frontal & Sagittal	Whole
Smith (2017)	TJA	"Distance from subjects to allow full coverage of jumps"		Frontal & Sagittal	Whole
Stroube (2013)	TJA	Unknown	Unknown	Frontal & Sagittal	Whole

ASIS: Anterior Superior Iliac Spine, DVJ: Drop Vertical Jump, F: Frontal, LL: Lower Limb, m: meters, S: Sagittal, SLL: Single-leg Land, SLS: Single-leg Squat, SLSD: Single-leg Step Down, SLVDJ: Single-leg Vertical Drop Jump, TJA: Tuck Jump Assessment

Initially, a camera distance of 3.5m was selected as it had been utilised in previous work and was considered a more viable distance for camera positions across different testing spaces. In addition, the majority of the aforementioned research (table S1) had only captured 2D variables from a frontal plane. This study intended to capture multiple 2D variables from the frontal and sagittal planes, resultantly greater space was needed to ensure capture of the desired movement planes. Pilot work was completed across multi-centre sites, within testing venue one (dance school) the allocated testing space was 3.5m x 5m, which only allowed for a distance of 3m x 3m with camera and kit positioning. In test venue two (ice-rink), space was slightly larger at 4m x 6m. Pilot filming from both test venues at 3m (dance school) and 3.5m (ice-rink) were compared. 3m was deduced sufficient enough for video capture quality, as well as practically appropriate for a clinical space.

In previously examined research camera were wither wall or tripod mounted. The height of camera placement also varied between studies and was reported from 0.3m-1.2m. A search of the literature had highlighted the absence of research evaluating the trunk and upper limb within the whole movement pattern. Inclusion of these body segments was a key aim of this study, and therefore the methods of (Dingenen *et al.*, 2014, 2015) were initially piloted. A camera height of 0.6m was chosen as this had previously been shown as sufficient for capturing all body segments during the SLS and for participants <170cm during SLL and TJA. With a camera height of 0.6m, participants >173cm in height, frequently jumped out of shot during the TJA (figure S1) and had op of shoulders, neck and head out of shot when stood on the plyo box for landing. As such full coverage of jumps and lands was unable to be completed. The majority of TJA papers do not report camera height, some fix to an anatomical landmark that varies to each participant (I.e. ASIS, waist height). To further improve the practical application of this methodology, camera height also had to be addressed. The use of anatomical landmarks was a concern around whole movement capture, and the impact on reliability if a camera set up required changing between each participant and task. To improve time efficiency for both raters and participants, and to allow for smoother testing procedure to be run as a test battery, selection of a standardised camera height that would allow successful video capture during all three movement assessment tasks was adopted.

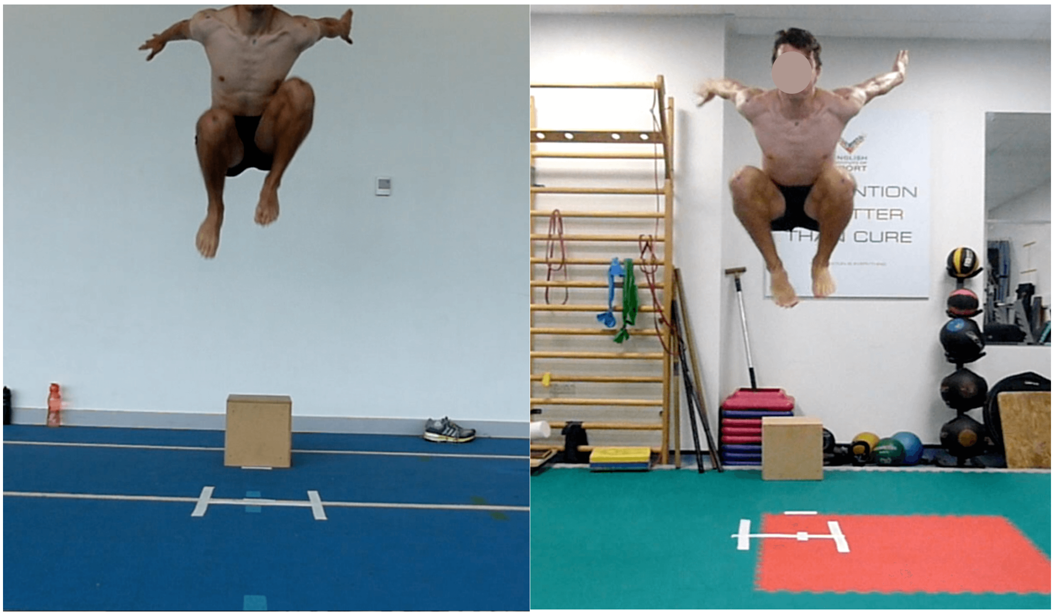


Figure S1 – Example of camera distance at 3m on participant >173cm (left) 0.6m height and (right) 0.7m height

Only one paper reported camera distance and height (Read *et al.*, 2016) when collecting the TJA from a sagittal and frontal plane. The authors recommended a camera height of 0.7m but a camera distance of 5m from the participant testing space. It had already been established that 5m was too great a distance in some of the available testing sites. A second pilot filming session was run using the pre-determined 0.7m height. The smallest (1.53m) and the tallest (1.89m) athletes were re-filmed with the new set-up, which provided full coverage of all required body segments across all three movement assessment tasks. The distance and camera height set-ups for subsequent testing were established during this way.

Supplementary B: Lateral Trunk Lean

The frontal 2D parameters of FPPA, Hip adduction angles, lateral trunk lean, shoulder abduction and sagittal 2D parameters of ankle dorsiflexion angle, knee flexion angle, hip flexion angle, trunk flexion angle and shoulder flexion/extension were selected as it was considered they might best replicate the individual QASLS components of the qualitative criteria. Previous literature (Padua *et al.*, 2009; Munro, Herrington and Carolan, 2012; Herrington *et al.*, 2017; Schurr *et al.*, 2017) was used to construct the methodology of the FPPA, HADD, ADF, KFA 2D variables. Documentation of torso measurement was less prevalent with only five papers (Edmondston *et al.*, 2013; DiCesare *et al.*, 2014; Dingenen *et al.*, 2014, 2015; Schurr *et al.*, 2017) reporting on trunk position capture via 2D or 3D methods, and all were limited to the single-leg squat or vertical drop jump movement assessment tasks.

To evaluate trunk and pelvic plane position, the methods of Edmondston *et al.* (2013) were attempted (figure S2). The authors measured femoral pelvic angle from a line joining the bilateral ASIS and a line extending from the ipsilateral ASIS to the lateral femoral condyle. Lateral trunk lean was measured by the same authors by a vertical and a line bisecting the midpoints of the ASIS and the AC process. This methodology was possible using the ImageJ software selected by the authors, this method was unable to be recreated using the Quintec software selected for this study. During their movement assessment tasks, Edmondston *et al.* (2013) standardised squat depth to only 30°. Since movements of the torso at this squat depth are small, it was also thought this method of assessment for trunk lean might not be representative of the depths required for the unrestricted single-leg squat and single-leg land movement assessment tasks that would be used within this study. The Edmondston *et al.* (2013) method was therefore discounted.

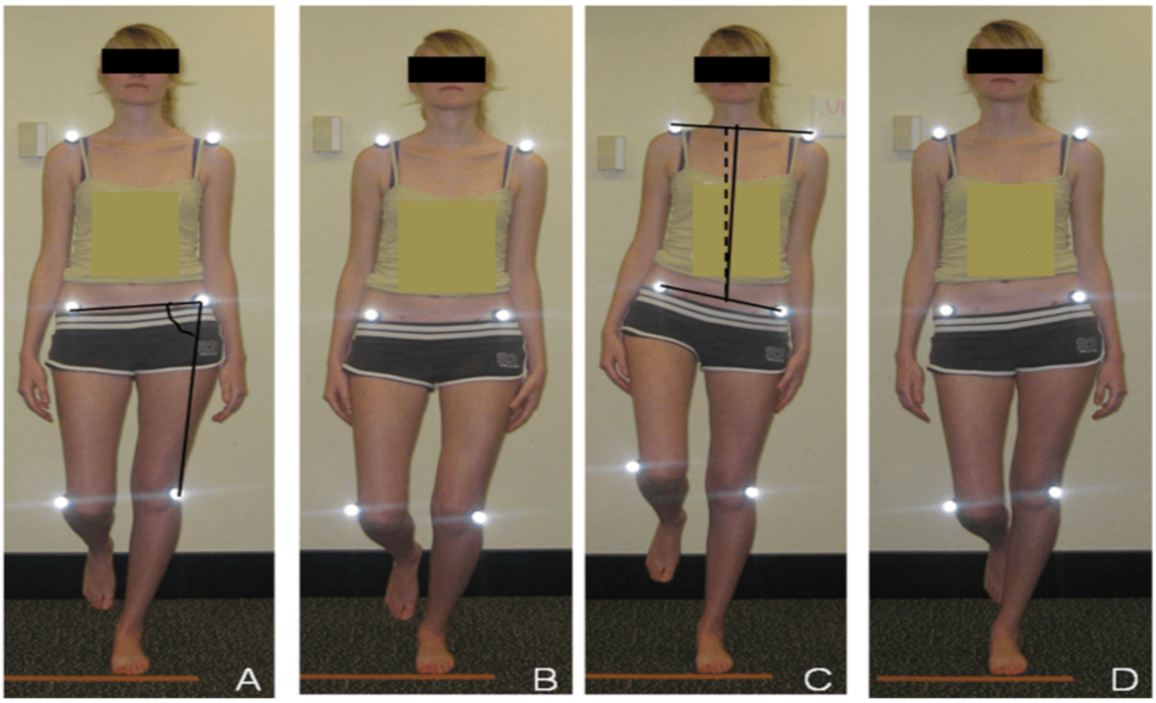


Figure: S2 Example of TFA and FPPA as via (Edmondston *et al.*, 2013) *methods, used without permission*

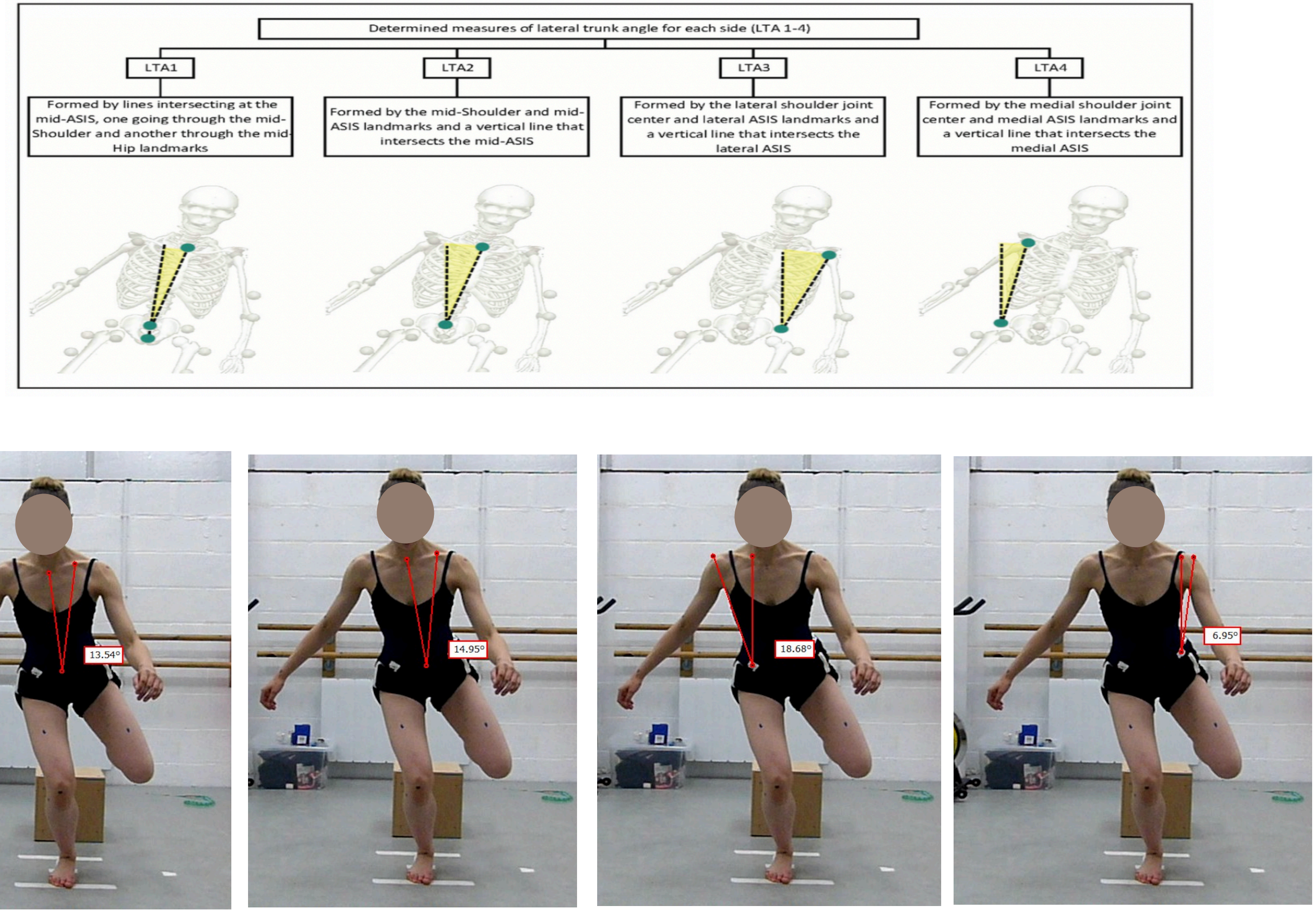


Figure: S3 Example of Trunk Lean LTA1-LTA4 Taken from DiCesare (2014) methods Leaning towards stance leg (used without permission)

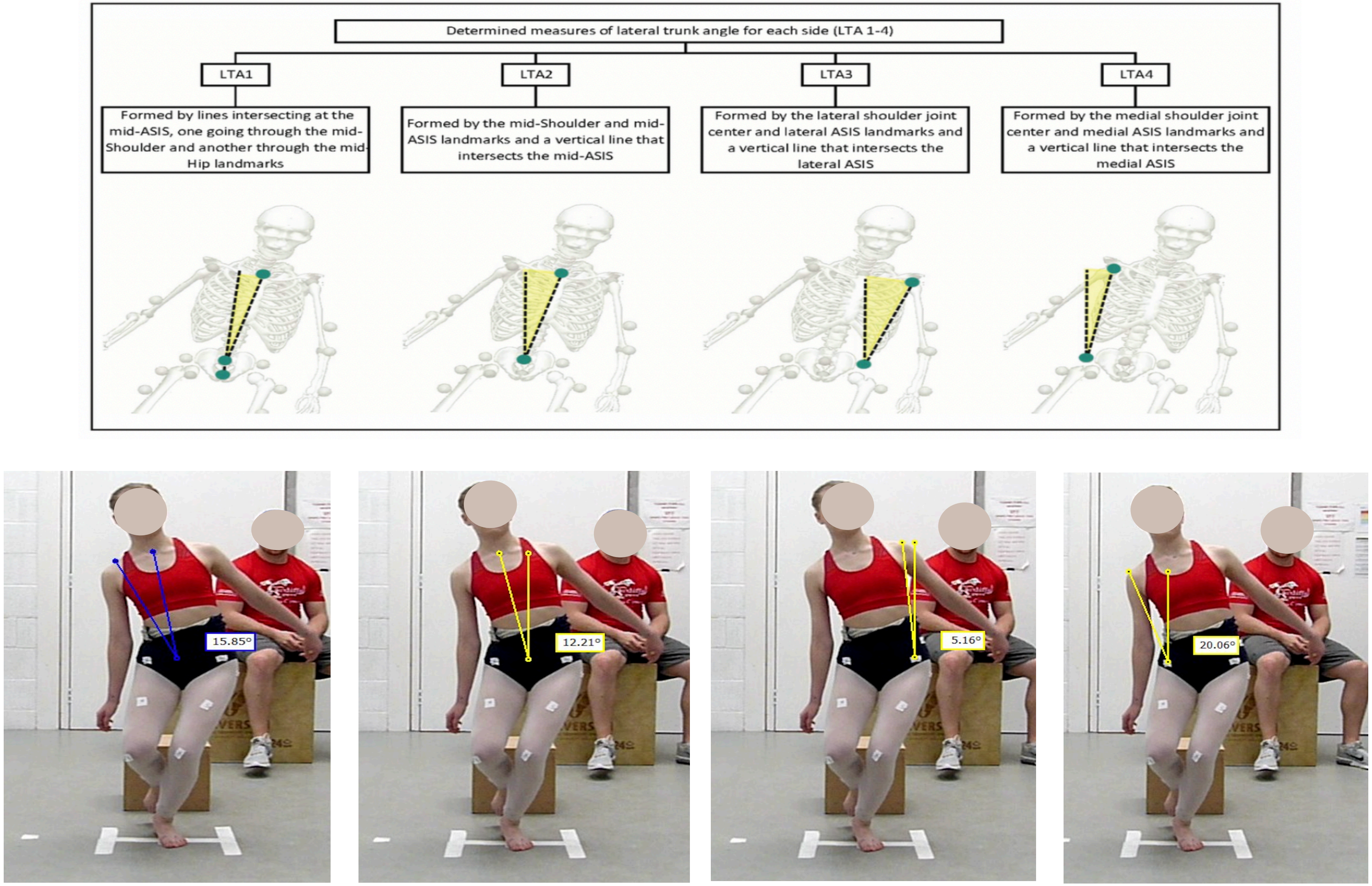


Figure - S4 Example of Trunk Lean LTA1-LTA 4 Taken from DiCesare (2014) Methods leaning away from stance leg (used without permission)

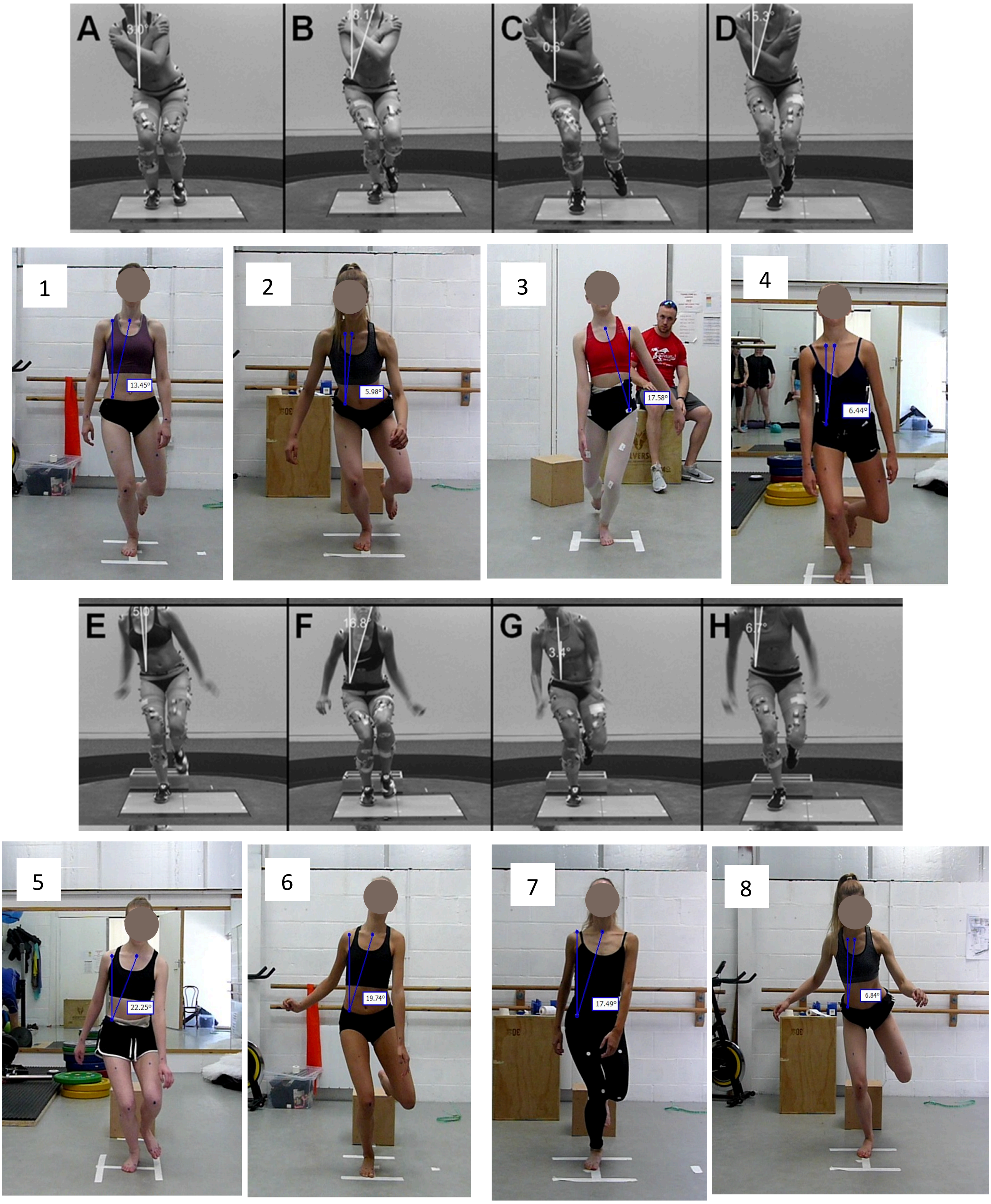


Figure: S5 Examples of Lateral Trunk Lean (LTL) during performances of Single-leg Squat (SLS) (A-D) taken from (Dingenen et al.; (2014) (1-4) Pilot subjects, and Single-leg Land (SLL) (E-H) taken from (Dingenen *et al.*, 2014) *(5-8) Pilot Subjects. Smaller LTL angles towards supporting leg represent more LTL, larger LTL angles away from supporting leg represent more LTL.*

Dingenen *et al.* (2014) captured lateral trunk motion during a single-leg squat and single-leg vertical jump. Lateral trunk motion was defined as the angle between a vertical line from the ipsilateral ASIS and the line between the ipsilateral ASIS and manubrium sterni (Figure S3). DiCesare *et al.* (2014) and colleagues demonstrated similar methods when comparing 2D trunk lean to 3D calculations during a single-leg cross drop landing, by using ASIS and shoulder landmarks.

The movement towards the landing leg was defined as lateral trunk motion, movement away from the landing leg was defined as medial, with maximal lateral trunk angle medial trunk angle and lateral trunk angle range of motion reported at the initial contact of landing. 2D data was calculated from the 3D measurements with DiCesare *et al.* (2014) deducing that lateral trunk measurements that were calculated using the medial shoulder joint centre.

Supplementary C: Upper Limb Position

There appears to be minimal research pertaining to 2D measurement specifically of the UL. Even within the purported gold standard 3D literature, GHJ motion is notoriously difficult to capture (Cutti, Cappello and Davalli, 2006; Khadilkar *et al.*, 2014). The establishment of upper limb joint centres are open to considerable error, with 35° of soft tissue artefact in humeral internal/external rotation (Cutti, Cappello and Davalli, 2006). Research regarding the upper limb infrequently limited to isolated monoplane movement, (Khadilkar *et al.*, 2014), reported in neurodegeneration conditions (Schwarz *et al.*, 2019) or whole upper limb evaluation of movement chains is limited to a few studies around gait (Khadilkar *et al.*, 2014). Devising an upper limb 2D measurement protocol for this study was challenging.

Only one paper (Khadilkar *et al.*, 2014) appeared to evaluate multiplanar upper limb movements via 2D analysis across multiple tasks. Ten healthy participants were captured from the sagittal and coronal plane performing five daily tasks with their dominant arm (such as opening a jar, pushing open a door and washing their hair). The researchers monitored shoulder flexion and abduction and reported high inter-individual task variability (ICC = 0.45-0.94) and moderate to excellent agreement on inter-rater reliability (ICC =0.68-1.0). Reflective markers were placed at C7, Superior ACJ, midway between medial and lateral humeral epicondyles (posterior), and dorsally midway between radial and ulnar styloid and 3rd metacarpal head.

Due to this study selecting frontal and sagittal movement planes for evaluation not sagittal and coronal, the ACJ, lateral epicondyle and radial styloid were initially selected as marker points due to direct visibility of these areas from the frontal and sagittal views. Upper limb range was measured from the ACJ to the wrist. Whilst this was initially successful during the SLS, when piloted during the SLL task, due to greater use of UL strategies by participants that utilised a bend at the elbow. Frequently resulted in obscuring of the lateral epicondylar marker and a questionable measurement (figure S6) as the long-lever was disrupted. A modification in the distal marker position was made, Khadilkar *et al.* (2014) selected an olecranon marker for the elbow to capture the posterior view, based on this the olecranon marker was adopted for the frontal view into the cubital fossa (defined as the mid-point between medial and lateral epicondyles) to create a shorter lever approach. This enabled abduction to be captured during all tasks as it wasn't dependant on the lower portion of the upper limb.

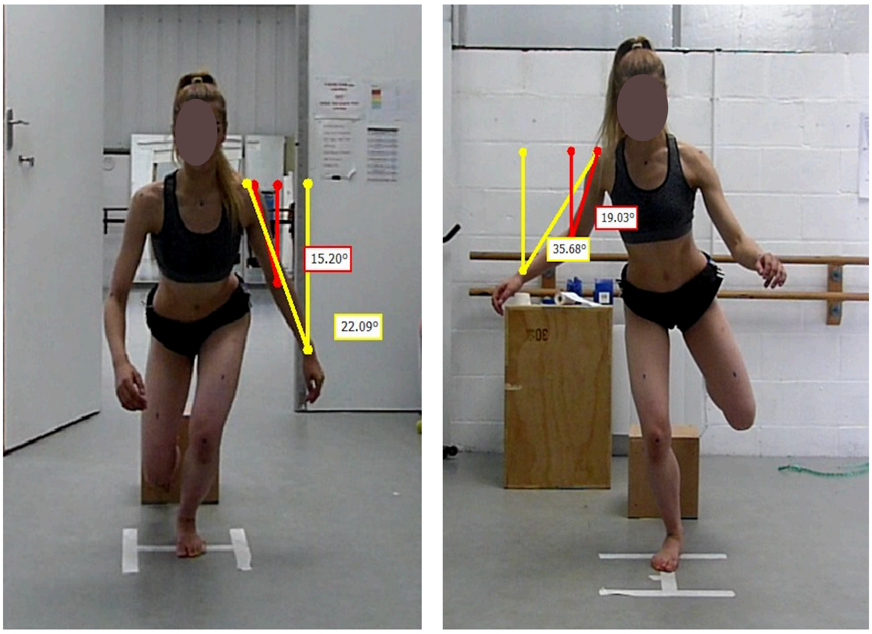


Figure S6: Example of SLS with long lever marking and short lever marking (Left Photo), SLL with long lever – line broken due to bent elbow and short lever marker (Right Photo)

Supplementary D: Marked Vs Un-Marked Participants

When approaching prospective testing groups, a potential limitation to participation was the application of markers. Despite original marker numbers being reduced post-pilot (Figure S7-S8) and application taking around 5 minutes, certain groups would only consent to partake if markers were not a requirement. To encourage maximal uptake of participant contribution, it was important to establish if 2D measurement and qualitative scores could be consistently scored without markers. Secondly, to expedite the testing process to allow qualitative scoring of 2D videos it was also important to investigate if 2D markers affected scoring of the qualitative criteria, as qualitative visual assessment would usually occur in an unmarked state.

Pilot work was completed with three raters of different experience. Rater 1 classified as an expert rater with extensive experience (>15 years) of 2D analysis and conceiver of the qualitative assessment tool. Rater 2 classified as experienced having 4 years' experience of the qualitative assessment tool and 5 years of 2D analysis. Rater 3 as a novice rater having no experience of the qualitative tool and less than a years' experience of 2D analysis.

An adult female participant was filmed completing the three-movement assessment tasks of SLS, SLL and TJA. An hour later the participant was filmed completing the same tasks in the same order with the markers in-situ. Raters 1 and 3, who were not advised of the nature of the pilot work, were requested to complete the task again in the same way, however, the videos were changed to the participant in the marked condition. Rater 2 was unable to be blinded to the nature of the marked/unmarked state of the participant, as they were completing the rater assessment. However, a month between scoring trials was deemed adequate to mitigate for rater 2 being unblinded to results. Intra and inter-rater QASLS scores were established via the percentage of exact agreement (PEA), where PEA=(agreed/agreed+ disagreed) x100.

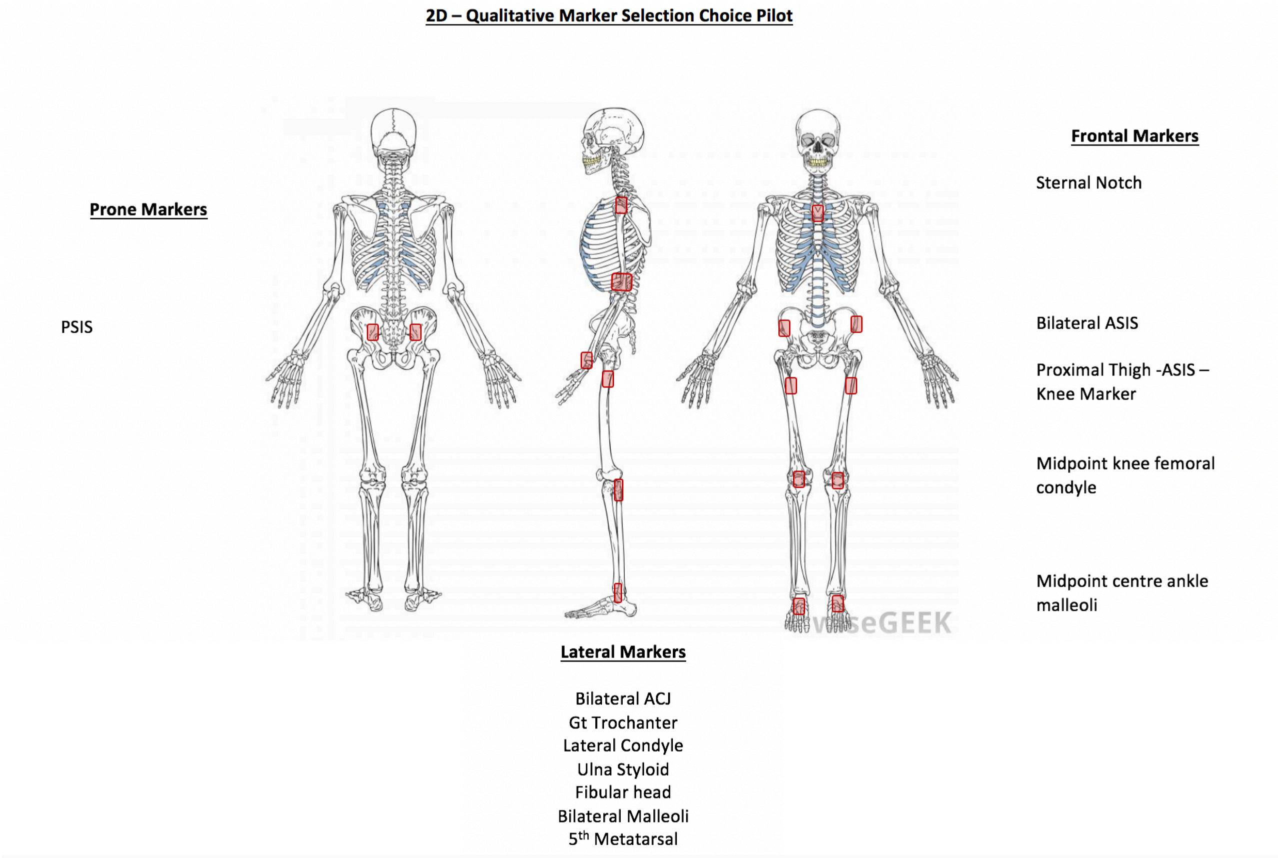


Figure S7-: Pilot 2D marker selection

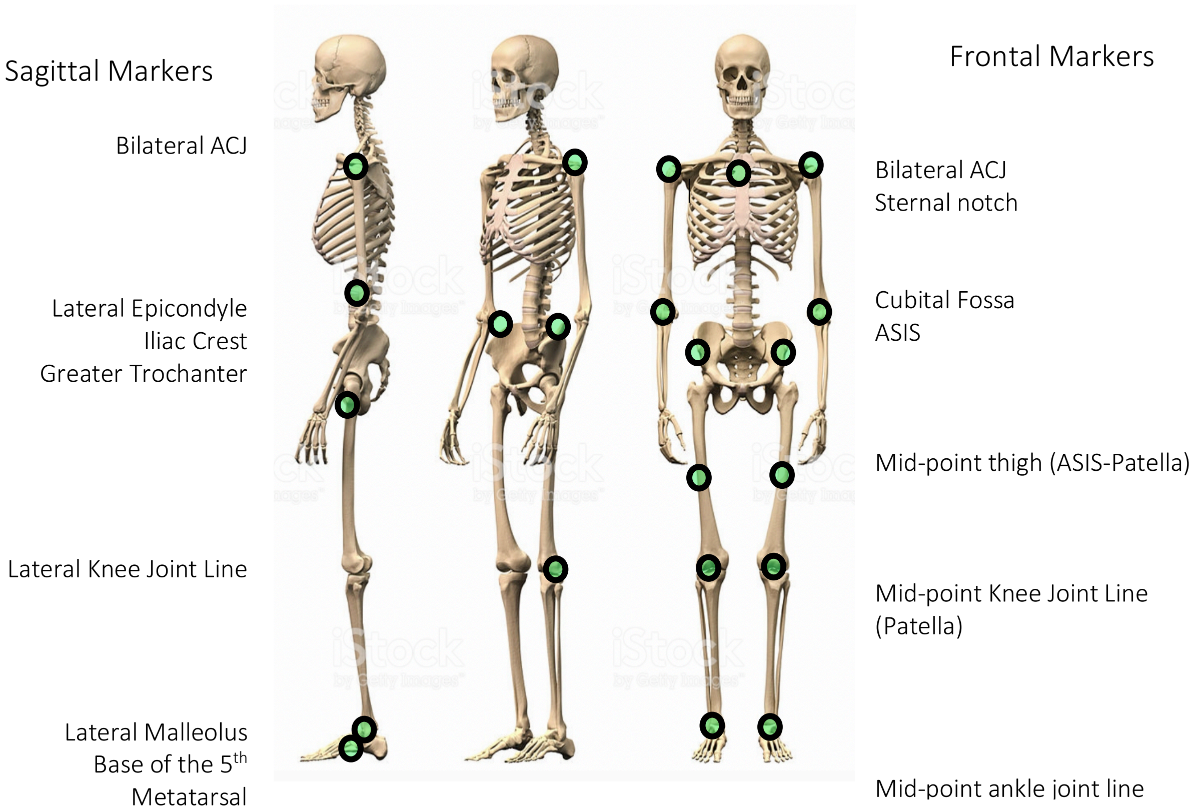


Figure S8 - Final 2D anatomical marker selection

Inter-Rater Average PEA between the three raters across all the scoring criteria was good to excellent (73%-87%). Raters were in 100% agreement across 8/10 of the scoring components for SLS (table S2) and 6/10 for SLL (table S3). In single-leg squat, the least experience rater disagreed with 1 point concerning pelvic rotation. In the single-leg land tasks, the most experienced rater disagreed with the moderately experienced and novice level experienced raters during pelvic rotation, and the least experienced rater disagreed with the expert and moderately experienced raters on DKV, SKV and stance leg that wobbles. Compound scoring was the same between both the unilateral tasks and the unmarked and marked condition across all three raters, demonstrating that 2D markers do not appear to influence compound qualitative scoring. Figure S8 demonstrates the final marker selection.

Intra-Rater reliability for each rater was 100% between the marked and unmarked condition (table S4) for both the single-leg squat & single-leg land tasks – suggesting that qualitative assessment markers did not affect individual criteria of QASLS score, potentially regardless of the experience of scoring criteria.

Table S2 – PEA% for SLS across 3 raters

QASLS Component	R1/R2	R1/R3	R2/R3	Agreement
Arm	1	1	1	3/3
Trunk	1	1	1	3/3
Pelvic Drop	1	0	0	1/3
Pelvic Rotation	1	0	0	1/3
Hip Adduction	1	1	1	3/3
NWB Leg	1	1	1	3/3
Noticeable Knee Valgus	1	1	1	3/3
Significant Knee Valgus	1	1	1	3/3
NWB Touch Down	1	1	1	3/3
Stance Leg Wobble	1	1	1	3/3
			PEA	87%

NWB= none weight bearing, PEA%= Percentage of exact agreement, QASLS = Qualitative assessment of single-leg loads, R= Rater

Table S3 – PEA% for SLL across 3 raters

QASLS Component	R1/R2	R1/R3	R2/R3	Agreement
Arm	1	1	1	3/3
Trunk	1	1	1	3/3
Pelvic Drop	1	1	1	3/3
Pelvic Rotation	0	0	1	1/3
Hip Adduction	1	1	1	3/3
NWB Leg	1	1	1	3/3
Noticeable Knee Valgus	1	0	0	1/3
Significant Knee Valgus	1	0	0	1/3
NWB Touch Down	1	1	1	3/3
Stance Leg Wobble	1	0	0	1/3
			PEA	73%

NWB= none weight bearing, PEA%= Percentage of exact agreement, QASLS = Qualitative assessment of single-leg loads, R= Rater

Table S4 – PEA% across QASLS components for un-marked and marked participants

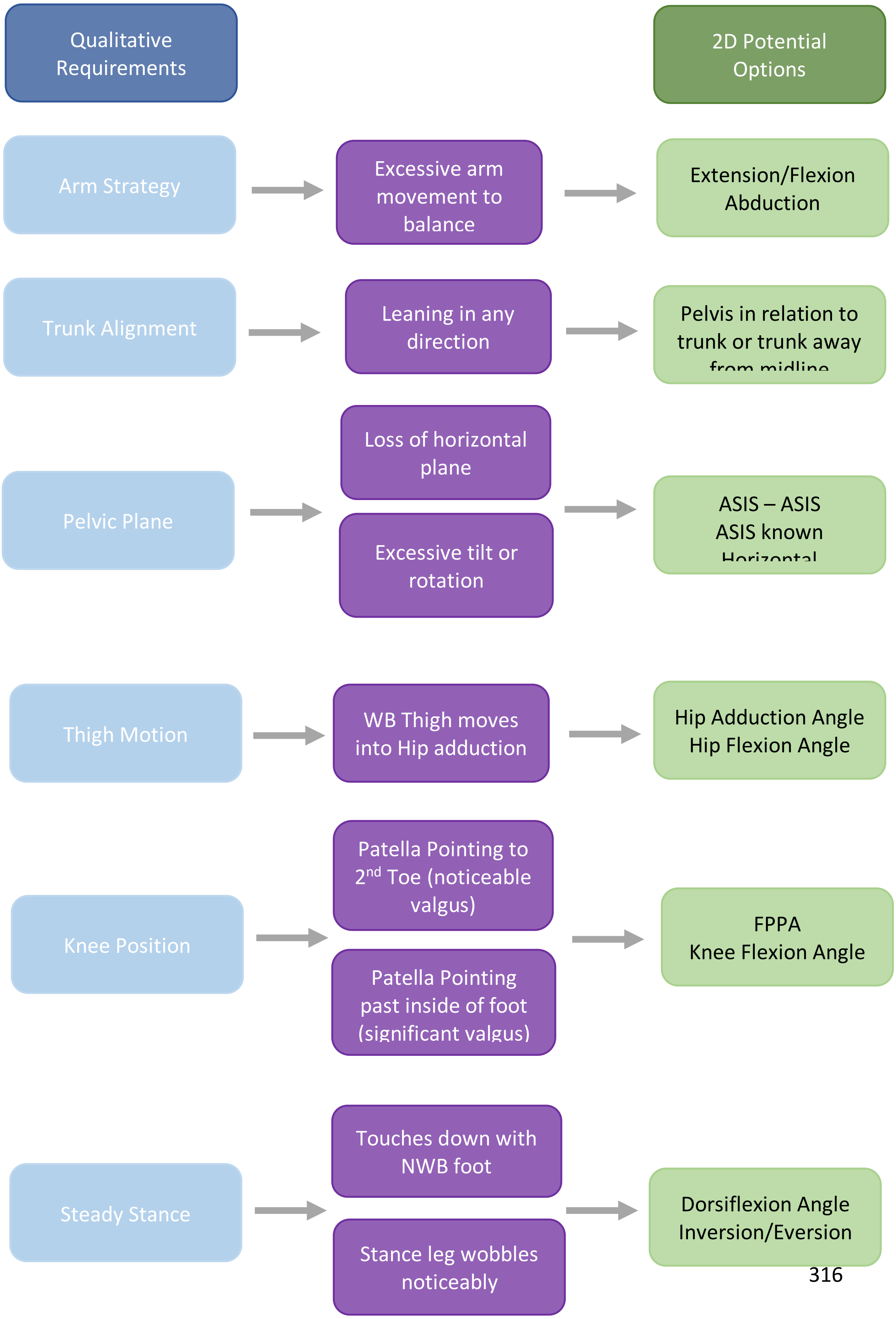
Task		QASLS components																				
SLS		Arm		Trunk		Pelvic Drop		Pelvic Rotation		Hip ADDN		NWB Hip		NKV		SKV		Touch Down		Stance leg wobbles		Compound Score
Rater	Condition	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	
R1	Unmarked	1		1		1			1	1			1	1			1		1	1		6
R2		1		1		1			1	1			1	1			1		1	1		6
R3		1		1			1	1		1			1	1			1		1	1		6
R1	Marked	1		1		1			1	1			1	1			1		1	1		6
R2		1		1		1			1	1			1	1			1		1	1		6
R3		1		1			1	1		1			1	1			1		1	1		6
SLL		Arm		Trunk		Pelvic Drop		Pelvic Rotation		Hip ADDN		NWB Hip		NKV		SKV		Touch Down		Stance leg wobbles		Compound Score
Rater	Condition	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	
R1	Unmarked	1		1		1			1	1		1			1	1		1		1		8
R2		1		1		1		1		1		1			1	1		1		1		8
R3		1		1		1		1		1		1		1			1		1		1	8
R1	Marked	1		1		1			1	1		1			1	1		1		1		8
R2		1		1		1		1		1		1			1	1		1		1		8
R3		1		1		1		1		1		1		1			1		1		1	8

ADDN= Adduction, NKV= noticeable Knee Valgus, R= Rater, SKV= significant knee valgus, SLL = single-leg land, SLS= single-leg squat

<u>Appendix A: Literature Review Search Terms</u>

1. biomechanics.mp. [mp=ti, ab, tx, ct, sh, bt, hw, id, tc, ot, tm, mh, nm, fx, kf, ox, px, rx, an, ui, ds, on, sy]
2. lower limb.mp. [mp=ti, ab, tx, ct, sh, bt, hw, id, tc, ot, tm, mh, nm, fx, kf, ox, px, rx, an, ui, ds, on, sy]
3. 1 and 2
4. functional analysis.mp. [mp=ti, ab, tx, ct, sh, bt, hw, id, tc, ot, tm, mh, nm, fx, kf, ox, px, rx, an, ui, ds, on, sy]
5. movement analysis.mp. [mp=ti, ab, tx, ct, sh, bt, hw, id, tc, ot, tm, mh, nm, fx, kf, ox, px, rx, an, ui, ds, on, sy]
6. motion analysis.mp. [mp=ti, ab, tx, ct, sh, bt, hw, id, tc, ot, tm, mh, nm, fx, kf, ox, px, rx, an, ui, ds, on, sy]
7. kinematic analysis.mp. [mp=ti, ab, tx, ct, sh, bt, hw, id, tc, ot, tm, mh, nm, fx, kf, ox, px, rx, an, ui, ds, on, sy]
8. 2 and 4 and 5 and 6 and 7
9. 2 or 4 or 5 or 6 or 7
10. 3D motion analysis.mp. [mp=ti, ab, tx, ct, sh, bt, hw, id, tc, ot, tm, mh, nm, fx, kf, ox, px, rx, an, ui, ds, on, sy]
11. 2D motion analysis.mp. [mp=ti, ab, tx, ct, sh, bt, hw, id, tc, ot, tm, mh, nm, fx, kf, ox, px, rx, an, ui, ds, on, sy]
12. video analysis.mp. [mp=ti, ab, tx, ct, sh, bt, hw, id, tc, ot, tm, mh, nm, fx, kf, ox, px, rx, an, ui, ds, on, sy]
13. observational analysis.mp. [mp=ti, ab, tx, ct, sh, bt, hw, id, tc, ot, tm, mh, nm, fx, kf, ox, px, rx, an, ui, ds, on, sy]
14. movement screen.mp. [mp=ti, ab, tx, ct, sh, bt, hw, id, tc, ot, tm, mh, nm, fx, kf, ox, px, rx, an, ui, ds, on, sy]
15. 10 and 14
16. lower extremity.mp. [mp=ti, ab, tx, ct, sh, bt, hw, id, tc, ot, tm, mh, nm, fx, kf, ox, px, rx, an, ui, ds, on, sy]
17. reliability.mp. [mp=ti, ab, tx, ct, sh, bt, hw, id, tc, ot, tm, mh, nm, fx, kf, ox, px, rx, an, ui, ds, on, sy]
18. single leg squat.mp. [mp=ti, ab, tx, ct, sh, bt, hw, id, tc, ot, tm, mh, nm, fx, kf, ox, px, rx, an, ui, ds, on, sy]
19. single leg land.mp. [mp=ti, ab, tx, ct, sh, bt, hw, id, tc, ot, tm, mh, nm, fx, kf, ox, px, rx, an, ui, ds, on, sy]
20. tuck jump assessment.mp. [mp=ti, ab, tx, ct, sh, bt, hw, id, tc, ot, tm, mh, nm, fx, kf, ox, px, rx, an, ui, ds, on, sy]
21. 10 or 11 or 18 or 19 or 20
22. 11 and 18 and 19 and 20
23. 10 and 18 and 19 and 20
24. 7 or 18 or 19 or 20
25. 17 and 24
26. 2 and 25

Appendix B: Potential Motion Analysis comparable to QASLS



Appendix C – Older and Younger Participant Instructions

QASLS instructions

Single leg squat

Stand on the mark with your arms relaxed by your sides, bend your none stance leg to 90 degrees as if you were lifting your heel towards your bum keeping it by the side of your test leg. When asked complete 5 squats as if you were going to sit on a chair, return to the start position, before completing the next repetition.

Single leg landing

Stand in the middle of the box, step forward off the box landing onto your test leg and stick the landing for 3 seconds. Once completed walk around the side of the box and step on from the back to return to the start position. Please repeat till you have completed 5 lands

Age appropriate Instructions for u10s (as approved by Prof T Long)

Single Leg Squat

Stand on the mark with your arms loose by the side of your body. Stand on one leg, bend the leg that you are not standing on at the knee so your toes point to the floor and your heel is towards your bottom. Imagine you are sitting backwards onto a seat using the leg you are standing on. Keep your movement nice and smooth and steady.

Single Leg Land

Stand on the box both feet together arms nice and loose at the side of your body. Show me the leg you will land on. Step off the box onto that leg, hold the position where you land for a count of three in your head.

Appendix D – Descriptive statistics for 2D kinematic variables for whole, pre and circa-PHV groups during two unilateral tasks

Descriptive statistics for between session consistency SLS 2D parameters for whole group data

FRONTAL PARAMETERS	TEST 1 (°)	TEST 2 (°)	ICC	CV%	95% (CI)	SEM (°)	SDD
Shoulder Abduction Right Limb	23.7 ± 16.9	21.2 ±14.7	0.57	40.4	0.05-0.85	10.3	28.6
Left Limb	23.9 ± 16.4	22.6± 18.9	0.81	31.7	0.49-0.94	7.7	21.3
Lateral Trunk Lean Right Limb	32.5 ± 10.6	33.7 ± 10.0	0.59	13.6	0.08-0.85	6.6	18.3
Left Limb	28.3 ± 8.0	29.2 ± 7.6	0.75	9.3	0.36-0.92	3.9	10.8
Hip Adduction Right Limb	59.2 ± 8.1	59.8 ± 9.7	0.06	11.1	-0.49-0.57	8.7	24.1
Left Limb	70.4 ± 10.3	66.4 ± 11.3	0.38	9.6	-0.19-0.76	8.5	23.7
FPPA Right Limb	25.0 ± 8.4	21.3 ± 8.8	0.16	29	-0.41-0.64	7.9	21.9
A Left Limb	16.3 ± 8.1	18.3 ± 10.2	0.52	30.7	-0.02-0.82	6.3	17.6
SAGITTAL PARAMETERS							
Shoulder Extension Right Limb	35.6 ± 33.8	30.8 ± 32.9	0.67	29.5	0.53-0.94	19.0	52.8
Left Limb	34.7 ± 32.4	35.1 ± 34.4	0.79	30.8	0.44-0.93	15.2	42.1
Trunk Flexion Angle Right Limb	43.8 ± 19.3	45.7 ± 18.8	0.82	16.9	0.51-0.94	8.1	22.4
Left Limb	42.1 ± 20.4	42.2 ± 18.3	0.90	12.7	0.71-0.97	6.2	17.1
Hip Flexion Angle Right Limb	99.0 ± 29.3	96.7 ± 29.8	0.81	10.3	0.49-0.94	12.9	35.6
Left Limb	101.6 ± 32.0	97.6 ± 31.5	0.85	10.6	0.58-0.95	12.5	34.6
Knee Flexion Angle Right Limb	100.8 ± 11.0	99.7 ± 12.7	0.74	5.1	0.34-0.91	6.3	17.4
Left Limb	102.6 ± 14.1	100.2 ± 14.1	0.66	6.2	0.20-0.88	8.3	23.0
Ankle Dorsiflexion Right Limb	58.0 ± 4.7	57.5 ± 5.1	0.74	3.7	0.34-0.91	2.5	7.0
Left Limb	58.8 ± 6.1	57.6 ± 5.2	0.65	4.2	0.18-0.88	6.4	9.4

Descriptive statistics for between session consistency for SLL 2D parameters for whole group data

FRONTAL PARAMETERS	**TEST 1 (°)**	**TEST 2 (°)**	**ICC**	**CV%**	**95% (CI)**	**SEM (°)**	**SDD**
Shoulder Abduction Right Limb	20.7 ± 16.8	22.9 ± 15.1	0.83	29.8	0.53-0.94	6.6	18.3
Left Limb	22.0 ± 14.4	19.8 ± 13.6	0.74	24.5	0.34-0.91	7.2	19.8
Lateral Trunk Lean Right Limb	27.2 ± 6.0	27.3 ± 5.3	0.52	8.0	-0.02-0.82	3.9	10.9
Left Limb	25.7 ± 5.9	24.9 ± 6.3	0.33	13.8	-0.25-0.73	5.0	13.9
Hip Adduction Right Limb	72.8 ± 8.1	72.7 ± 8.9	0.30	6.9	-0.28-0.72	7.1	19.7
Limb	80.4 ± 7.9	77.9 ± 9.0	0.41	6.5	-0.16-0.77	6.5	18.0
FPPA Right Limb	18.2 ± 8.1	17.7 ± 6.8	0.34	35.3	-0.23-0.74	5.5	15.3
Limb							
SAGITTAL PARAMETERS							
Shoulder Extension Right Limb	17.7 ± 15.2	17.3 ± 9.0	0.50	28.7	-0.04-0.82	8.9	24.6
Left Limb	18.2 ± 16.9	19.0 ± 16.0	0.78	36.0	0.42-0.93	7.7	21.3
Trunk Flexion Angle Right Limb	28.3 ± 12.0	31.6 ± 12.5	0.69	21.0	0.25-0.89	6.8	18.8
Left Limb	27.1 ± 13.1	28.7 ± 12.7	0.82	16.8	0.51-0.94	5.4	15.1
Hip Flexion Angle Right Limb	124.2 ± 19.4	119.1 ± 18.1	0.64	7.6	0.16-0.87	11.5	31.8
Left Limb	123.9 ± 21.1	119.6 ± 20.4	0.73	7.6	0.32-0.91	10.7	29.8
Knee Flexion Angle Right Limb	116.6 ± 12.6	118.1 ± 14.3	0.61	5.3	0.11-0.86	7.9	21.8
Left Limb	118.1 ± 14.3	115.1 ±11.1	0.49	6.8	-0.06-0.81	9.2	25.4
Ankle Dorsiflexion Right Limb	66.4 ± 5.9	66.0 ± 6.1	0.58	4.8	0.07-0.85	3.9	10.8
Limb	68.5 ± 7.1	65.8 ± 5.5	0.45	5.9	-0.11-0.79	4.7	13.0

Descriptive statistics for between session consistency SLS 2D parameters for Pre-PHV group data

FRONTAL PARAMETERS	**TEST 1 (°)**	**TEST 2 (°)**	**ICC**	**CV%**	**95% (CI)**	**SEM (°)**	**SDD**
Shoulder Abduction Right Limb	23.8 ± 18.8	23.7 ± 14.3	0.61	33.4	0.11-0.86	10.5	29
Left Limb	27.1 ± 22.6	28.7 ± 22.2	0.98	16.8	0.940.99	3.5	9.6
Lateral Trunk Lean Right Limb	30.9 ± 7.7	31.6 ± 9.6	0.73	9.8	0.32-0.91	4.6	12.6
Left Limb	26.0 ± 6.9	27.6 ± 6.8	0.81	8.5	0.49-0.94	3.0	8.2
Hip Adduction Right Limb	58.1 ± 8.0	60.5 ± 9.2	-0.25	12.6	-0.69-0.33	9.6	26.7
Left Limb	71.4 ± 9.6	69.5 ± 10.7	0.68	6.0	0.23-0.89	5.8	16.0
FPPA Right Limb	27.0 ± 7.2	20.2 ± 6.5	-0.29	30.6	-0.71-0.29	7.8	21.7
Left Limb	16.8 ± 7.3	17.0 ± 6.5	0.58	18.8	0.07-0.85	4.5	12.4
SAGITTAL PARAMETERS							
Shoulder Extension Right Limb	23.7 ± 18.7	20.8 ± 20.4	0.35	28.3	-0.22-0.74	12.4	34.3
Left Limb	28.9 ± 27.2	25.0 ± 22.8	0.85	31.5	0.58-0.95	9.7	26.8
Trunk Flexion Angle Right Limb	40.6 ± 16.6	41.3 ± 15.0	0.69	18.2	0.25-0.89	8.8	24.5
Left Limb	35.9 ± 17.1	38.4 ± 14.1	0.77	18.8	0.44-0.91	7.5	20.7
Hip Flexion Angle Right Limb	107.3 ± 25.1	108. ± 21.2	0.68	8.7	0.23-0.89	13.2	36.5
Left Limb	111.5 ± 25.2	105.8 ± 21.6	0.61	10.9	0.11-0.86	14.6	40.5
Knee Flexion Angle Right Limb	104.6 ± 10.1	105.8 ± 11.3	0.77	3.7	0.40-0.92	5.2	14.3
Left Limb	104.2 ± 12.5	103.7 ± 11.4	0.54	5.6	0.01-0.83	8.1	22.5
Ankle Dorsiflexion Right Limb	57.4 ± 6.1	57.6 ± 6.0	0.84	3.5	0.56-0.95	2.4	6.7
Left Limb	57.0 ± 7.5	56.5 ± 6.1	0.66	5.5	0.20-0.38	4.0	11.1

Descriptive statistics for between session consistency for SLL 2D parameters for Pre-PHV group

FRONTAL PARAMETERS	**TEST 1 (°)**	**TEST 2 (°)**	**ICC**	**CV%**	**95% (CI)**	**SEM (°)**	**SDD**
Shoulder Abduction Right Limb	24.8 ± 19.5	21.4 ± 16.2	0.90	28	0.71-0.97	5.6	15.6
Left Limb	25.0 ± 15.9	24.1 ± 15.6	0.65	27.2	0.18-0.88	9.3	25.9
Lateral Trunk Lean Right Limb	27.5 ± 7.9	25.8 ± 2.9	0.75	8.9	0.36-0.92	3.0	8.2
Left Limb	25.4 ±7.6	23.2 ± 3.1	0.52	14.9	0.20-0.82	4.0	11.2
Hip Adduction Right Limb	74.0 ± 7.1	72.0 ± 8.0	0.10	7.6	0.46-0.60	7.2	20.1
Left Limb	81.3 ± 6.0	75.3 ± 9.5	0.42	8.2	0.14-0.78	6.0	16.7
FPPA Right Limb	18.7 ± 8.7	18.2 ± 15.5	0.09	40.3	-0.38-0.66	8.0	22.3
A Left Limb	12.7 ± 8.2	13.5 ± 6.3	0.08	39.7	-0.39-0.65	7.0	19.5
SAGITTAL PARAMETERS							
Shoulder Extension Right Limb	21.9 ± 22.2	19.0 ± 8.7	0.57	31.1	0.05-0.85	11.1	30.9
Left Limb	20.7 ± 24	20.8 ± 20.3	0.76	30.7	0.38-0.92	10.9	30.3
Trunk Flexion Angle Right Limb	25.2 ± 12.4	27.0 ± 11.1	0.71	20.6	0.29-0.90	6.4	17.7
Left Limb	22.9 ± 12.6	23.8 ± 12.4	0.85	16.7	0.58-0.95	4.8	13.2
Hip Flexion Angle Right Limb	129.9 ± 21.3	127.3 ± 18.4	0.70	6.2	0.27-0.90	10.8	30.0
Left Limb	128.0 ± 20.8	126.5 ± 20.8	0.73	6.7	0.32-0.91	10.8	29.8
Knee Flexion Angle Right Limb	118.2 ± 13.9	120.8 ± 13.4	0.84	3.5	0.56-0.95	5.5	15.2
Left Limb	117.7 ± 12.9	118.2 ± 11.8	0.59	5.6	0.08-0.85	7.9	22.0
Ankle Dorsiflexion Right Limb	67.4 ± 5.0	68.2 ± 6.6	0.67	4.0	0.21-0.89	3.4	9.4
Left Limb	69.6 ± 5.8	67.6 ± 5.1	0.47	5.0	0.08-0.80	4.0	11.0

Descriptive statistics for between session consistency SLS 2D parameters for Circa-PHV group data

FRONTAL PARAMETERS	**TEST 1 (°)**	**TEST 2 (°)**	**ICC0.34**	**CV%**	**95% (CI)**	**SEM (°)**	**SDD**
Shoulder Abduction Right Limb	24.1 ± 16.1	20.7 ± 14.9	0.53	44.1	0.01-0.83	10.6	29.3
Left Limb	21.9 ± 9.4	19.0 ± 14.6	0.34	43.3	-0.23-0.74	10.0	27.7
Lateral Trunk Lean Right Limb	35.2 ± 13.3	36.9 ± 10.4	0.56	16.8	0.04-0.84	8.0	22.0
Left Limb	31.1 ± 9.0	31.4 ± 8.0	0.69	10.3	0.25-0.89	4.7	13.1
Hip Adduction Right Limb	61.3 ± 8.1	59.9 ± 9.8	0.28	8.9	-0.30-0.71	7.6	21.2
Left Limb	69.5 ± 11.5	62.6 ± 11.0	0.21	12.6	-0.36-0.67	10	27.7
FPPA Right Limb	23.2 ± 9.4	20.3 ± 8.4	0.59	24.9	0.08-0.85	5.7	15.7
Left Limb	16.7 ± 8.9	20.7 ± 11.6	0.48	32.3	-0.07-0.81	7.5	20.7
SAGITTAL PARAMETERS				-			
Shoulder Extension Right Limb	47.3 ± 40	44.0 ± 40	0.65	31.2	0.18-0.88	23.8	66.1
Left Limb	41.4 ± 36	44.9 ± 40.4	0.76	33.0	0.38-0.92	18.7	51.9
Trunk Flexion Angle Right Limb	48.6 ± 21.9	51.1 ± 21.3	0.88	14.9	0.65-0.96	7.6	21.1
Left Limb	48.9 ± 22.0	47.4 ± 21.0	0.95	9.6	0.84-0.98	5.0	13.8
Hip Flexion Angle Right Limb	89.8 ± 31.9	84.9 ± 33.0	0.84	12.2	0.56-0.95	12.9	35.7
Left Limb	91.4 ± 35.0	87.2 ± 36.3	0.92	10.4	0.76-0.97	10.4	28.7
Knee Flexion Angle Right Limb	98.1 ± 12.6	94.5 ± 12.1	0.70	6.1	0.27-0.90	6.8	18.9
Left Limb	101.5 ± 15.2	96.8 ± 15.6	0.71	6.6	0.29-0.90	8.4	23.2
Ankle Dorsiflexion Right Limb	59.1 ± 3.0	58.0 ± 4.2	0.54	3.8	0.01-0.83	2.5	6.8
Left Limb	60.7 ± 4.0	59.1 ± 4.3	0.41	3.8	-0.16-0.77	3.2	8.8

Descriptive statistics for between session consistency for SLL 2D parameters for Circa-PHV group

FRONTAL PARAMETERS	**TEST 1 (°)**	**TEST 2 (°)**	**ICC**	**CV%**	**95% (CI)**	**SEM (°)**	**SDD**
Shoulder Abduction Right Limb	20.8 ± 20.2	26.3 ± 16.7	0.89	30.8	0.68-0.97	6.1	17.0
Left Limb	22.3 ± 14.9	18.5 ± 12.5	0.82	22.7	0.51-0.94	5.8	16.0
Lateral Trunk Lean Right Limb	26.5 ± 4.9	26.8 ± 3.8	0.60	6.6	0.10-0.86	2.8	7.6
Left Limb	24.9 ± 4.7	24.2 ± 4.1	0.35	11.3	-0.22-0.74	3.5	9.8
Hip Adduction Right Limb	71.1 ± 8.6	74.2 ± 8.4	0.70	5.6	0.27-0.90	4.6	12.9
Left Limb	78.6 ± 8.9	80.3 ± 8.9	0.70	4.9	0.25-0.90	4.9	13.5
FPPA Right Limb	18.8 ± 9.1	19.0 ± 8.2	0.65	23.1	0.18-0.88	5.1	14.2
Left Limb	14.1 ± 7.8	14.0 ± 7.5	0.46	33.3	-0.10-0.80	5.6	15.6
SAGITTAL PARAMETERS							
Shoulder Extension Right Limb	19.8 ± 20.1	16.7 ± 10	0.57	26.5	0.05-0.85	10.4	28.8
Left Limb	22.7 ± 22.0	23.9 ± 20.2	0.79	45.2	0.44-0.93	9.5	26.6
Trunk Flexion Angle Right Limb	30.4 ± 11.1	33.9 ± 11.0	0.54	22.6	0.01-0.83	7.8	21.5
Left Limb	30.1 ± 13.5	32.2 ± 10.7	0.76	16.9	0.38-0.92	5.9	16.5
Hip Flexion Angle Right Limb	121.2 ± 17.6	115.1 ± 16.8	0.39	10.1	0.18-0.76	13.4	37.1
Left Limb	121.6 ± 23.4	114.0 ± 19.0	0.76	9.0	0.38-0.92	10.4	28.7
Knee Flexion Angle Right Limb	116.9 ± 10	113.2 ± 10.5	0.27	6.6	-0.31-0.70	9.1	25.3
Left Limb	119.8 ± 15.8	113.3 ± 10.1	0.42	8.0	-0.14-0.78	10.0	27.8
Ankle Dorsiflexion Right Limb	67.2 ± 5.6	65.9 ± 5.4	0.32	5.7	-0.26-0.73	4.6	12.6
Left Limb	69.4 ± 7.0	65.9 ± 5.4	0.15	7.4	-0.42-0.63	5.8	16.1

<u>Ethics Form</u>

University of Salford MANCHESTER

Research, Enterprise and Engagement
Ethical Approval Panel

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1 February 2018

Dear Gemma,

RE: ETHICS APPLICATION–HSR1718-033 – 'Reliability & Criterion Validity of Lower Limb Musculoskeletal Screening Tools.'

Based on the information that you have provided, I am pleased to inform you that ethics application HSR1718-033 has been approved.

If there are any changes to the project and/or its methodology, then please inform the Panel as soon as possible by contacting Health-ResearchEthics@salford.ac.uk

Yours sincerely,

Professor Sue McAndrew
Chair of the Research Ethics Panel

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