Intrinsic Risk Factors for Hip-Related Pain in Elite Rowers

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A thesis submitted in partial fulfilment of the requirements of the University of Salford for the degree of Doctor of Philosophy

April 2023

The University of Salford

School of Health Sciences

“Scientific knowledge is a body of statements of varying degrees of certainty … some most unsure, some nearly sure, none absolutely certain.”

Richard Feynman

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ACKNOWLEDGEMENTS

Firstly, I would like to thank my supervisor Dr Lee Herrington for all his support over the last few years. Your guidance, wisdom and dedication during this entire journey has been amazing. From helping me to scratch the itch when I was first considering getting into research to saying it like it is when I needed! You have always responded to my queries no matter how big or small, helped me navigate hurdles and distractions, guided me to think outside the box, and provided a level head to get me back on track when I lost my way. Thank you!

I would also like to extend my thanks to Dr James Martin for agreeing to come on board. Your input has been invaluable in helping to demystify statistics and giving me confidence to believe in my findings.

Thank you to the English Institute of Sport for giving me the opportunity to do this research, without their support this would not have been possible. Specifically, thanks to Julie Stark for helping me take the leap and making it happen, and to Jean Watson for working tirelessly to ensure I got the support I needed to juggle the world of elite sport and academia.

A huge thank you to the coaches and staff at British Rowing who have enabled and encouraged me to do this project. Thanks to the athletes who have willingly and happily participated in the screenings, and driven me to provide world leading medical support, just as they are striving to be the best in the world. An even bigger thanks to the individuals whose hips have sparked my curiosity and indirectly contributed to the learnings of this work.

To the amazing EIS and British Rowing support staff who work tirelessly in pursuit of helping others to achieve their dreams. I’m extremely grateful to Lawrence, Steve, Ben, Sam, Sally, Pat, Carol, Heather, and Batch, who have assisted with data collection, backed me up, and always supported me when I needed a hand. A special thanks to Dr Ann Redgrave who has been pivotal during my time at British Rowing, who always has time to share ideas over a cuppa around busy clinics or regatta finishing lines and has provided equal professional and emotional support throughout this journey.

A big thanks to Nicole, who always reminded me of my ‘why’ and for providing food, fresh-air, and friendship whenever I needed. And to the ‘smart girls’ club’, Gemma and Ros, for always being on hand for the pep talks, idea sharing and for inspiring me to aim high.

To my mum and dad who unknowingly provided the inspiration to do a PhD over Friday night homemade pizza and wine, whilst watching (and singing to) the BBT. For their unwaveringly support, proofreading and showing me that anything I wanted to do was possible. To my sister Jen, who has always had my back, looked after me, and encouraged me. Who, alongside my brilliant nephews and friends, have provided much needed distraction and motivation.

And finally, to Gaz who has been my rock throughout this journey. My cheerleader, my unofficial supervisor, my best friend. Who has invested as much time, energy, and wisdom into my PhD as he did his own. To say this would not have been possible without you is an understatement. And to our bump who’s given me the focus to get to the finish line. Looking forward to meeting you later this year!

GLOSSARY OF TERMS

ALT	Acetabular labral tear
ADLs	Activities of daily living
ANT	Anterior
AP	Anterior-posterior
ASIS	Anterior superior iliac spine
AUC	Area Under the Curve
CEA	Centre-edge angle
CHJP	Chronic Hip Joint Pain
CT	Computerised Tomography
DL	Double-leg
EA	Easyangle®
ETS	Electromagnetic Tracking System
EMG	Electromyography
ER	External rotation
FDT	Faber’s Distance Test
FABER	Flexion-abduction-external rotation
FADDIR	Flexion-adduction-internal rotation
FAI	Femoroacetabular Impingement
FAIS	Femoroacetabular Impingement Syndrome
FMS	Functional Movement Screen
GM	Gluteus Maximus
GT	Greater Trochanter
HHD	Hand-held Dynamometer
HAGOS	The Copenhagen Hip and Groin Outcome Score
HRP	Hip-related pain
IHiPRN	The International Hip-Related Pain Research Network
IAHI	Intra-articular hip injection
IAHP	Intra-articular hip pathology
IR	Internal rotation
IROP	Internal Rotation with Over Pressure
IHOT	International Hip Outcome Tool

ICC	Intraclass Correlation Coefficients
ID	Isokinetic Dynamometry
LBP	Low back pain
MRA	Magnetic Resonance Arthrography
MRI	Magnetic Resonance Imaging
MVC	Maximal voluntary contraction
MA	Medical Attention
MCS	Movement Competency Screen
ML	Medio-lateral
MDC	Minimal Detectable Change
mSEBT	Modified Star Excursion Balance Test
NPV	Negative Predictive Value
NR	Not reported
NTC	National Training Centre
OA	Osteoarthritis
PROs	Patient Reported Outcome Measures
PEA	Percentage of Exact Agreement
PL	Posterior-lateral
PM	Posterior-medial
PPV	Positive Predictive Value
PSIS	Posterior superior iliac spine
PRISMA	Preferred Reporting Items for Systematic Review and Meta-Analyses
QASLS	Qualitative Analysis of Single-leg Loading
QUADAS	Quality Assessment of Diagnostic Accuracy Studies
ROM	Range of motion
RFD	Rate of force development
ROC	Receiver Operating Characteristic
SL	Single leg
SLDJ	Single leg drop-jump
SLDL	Single leg drop-landing
STS	Sit to stand
STA	Soft Tissue Artefact
SEM	Standard Error of Measurement

SEBT	Star Excursion Balance Test
SLR	Straight leg raise
SN	Sensitivity
SP	Specificity
ST	Standing
SQ	Squat
TFL	Tensor fascia latae
THIRD	The Hip Internal Rotation with Distraction Test
TL	Time-loss
TRIPP	Translating Research into Injury Prevention Practice
US	Ultrasound
WB	Weight-bearing
YBT	Y-balance test
2D	2-dimensional
3D	3-dimensional
%LL	Percentage of leg length
+/- LR	Positive/negative Likelihood ratio

ABSTRACT

Background: The role of hip motion in relation to rowing performance has been well documented, yet the concept of hip health in rowers is poorly understood. In elite international rowing where high volumes of endurance training are critical to performance, injury prevention research is paramount to supporting both the health and performance of the individual.

Aim: The primary aim of this thesis was to the explore the association between intrinsic risk factors and hip-related pain (HRP) in a cohort of elite rowers. Furthermore, the thesis aimed to advance the understanding of HRP in elite rowers to inform the future screening and injury prevention practices.

Methods: A literature review was carried out examining the accuracy of clinical assessments in the diagnosis of femoroacetabular impingement syndrome (FAIS). A narrative review followed which explored both the physical and biomechanical presentations of individuals with HRP. This was used to identify potential risk factors and their assessments to inform the methodologies of the forthcoming chapters. Reliability of identified assessments was established, and standard error of measurements were quantified. A retrospective study was carried out to determine relationships between intrinsic risk factors and historical HRP in elite rowers, and to identify which factors were to be utilised in a further prospective study. This experimental chapter prospectively analysed the screening data of 55 elite rowers. Rowers were screened every six months over a course of two and a half seasons to ascertain which intrinsic, modifiable risk factors were associated with the development of HRP. Finally, a case report was carried out using the identified risk factors to ascertain whether a 3-month personalised exercise programme was able to positively influence both risk factors and injury incidence.

Results: The reliability of assessments used in the experimental chapters were deemed to be moderate to excellent for hip internal rotation (IR), 2-dimensional squat analysis, Y-balance assessments, single leg squat using a compound qualitative scoring system and isometric frontal plane hip strength using a hand-held dynamometer. Rowers with a history of HRP had shallower squat depths (HRP 52.5%; Control 50.5%) and reduced hip IR (HRP 40.4°; Control 37.1°). Furthermore, male rowers with a history of HRP had significantly smaller hip IR ranges (HRP 28.8°, Control 36.4°; $p \leq 0.05$). The prospective study identified that individuals who went on to develop HRP presented with smaller hip IR ranges of motion (mean difference (MD) = 2.4 – 7.8°), and shallower squat depths (MD = 3.9 – 6.3%) when compared with those without HRP. Both factors were also associated with increased risk of developing HRP and experiencing time-loss HRP injuries (IR OR: 0.86-0.92; Squat depth OR: 1.08-1.09). Key findings of the thesis were the differences found in physical and functional assessments between males and females. Males presented with smaller IR ranges and larger adduction strength and adduction:abduction strength ratios (p <0.01). In the subsequent case report, two rowers were identified as 'high-risk' for the development of HRP. Following a personalised exercise programme, no time-loss due to HRP was experienced and improvements in squat depth were seen (6-7%) and sustained over a 6-month period (4-9%).

Practical Implications: This thesis identified internal risk factors for the development of HRP in elite rowers. Although causation was not established, both risk factors have the potential to increase hip joint loading, which may lead to the development of pain and pathology. Results also provided initial evidence to support the role of exercise-based strategies in the prevention of HRP in elite rowers. The results of the thesis also highlight the importance of sex-specific screening protocols and management strategies in elite rowers. These findings should be investigated in larger cohorts of elite rowers to ascertain the predictive capabilities of these assessments.

COVID-19 IMPACT STATEMENT

Timeline of key events

On 31st December 2019, reports began to emerge of a new strain of pneumonia in China. On the 30th of January 2020, the World Health Organisation (WHO) declared a "public health emergency of international concern". By the 11th March 2020, the WHO announced a pandemic as a consequence of the **Covid-19** virus, a newly discovered coronavirus disease (Scally et al., 2020).

In the United Kingdom, on the 16th March, due to the growing concerns around the spread of infection and the consequent burden on the National Health Service (NHS), the public were asked to stop non-essential contact and travel. On the 21st March, **British Rowing** closed the doors to its national training centre sending elite athletes' home to train for an undefined period of time. The 23rd March 2020 saw the first of several national lockdowns, when people were ordered to "stay at home" (*Timeline of UK coronavirus lockdowns, March 2020 to March 2021*). By the 24th March 2020 the **Tokyo 2020 Olympic Games** were postponed for a year.

As of the 5th May 2021, the UK had confirmed more than 4.4 million cases of Covid-19 and 127,543 deaths as a result. Globally confirmed cases of more than 154 million with the number of deaths in excess of 3,227,968 (WHO, 2021).

"We may all be in the same storm, but we are not all in the same boat"

Damian Barr, 2021

Personal experience

The Covid-19 pandemic affected us all, in different ways to different degrees. Overall, I was fortunate that my personal experience during the pandemic was one of health and job security. But like many, work: life balance was challenging. Juggling working from home, a full-time job, and a part-time PhD, without the usual opportunities to reset and recharge. Not only did the pandemic curb my ability to collect data, but I also experienced a notable reduction in the time available to study. Consequently, this put me behind my predicted timeline for completion of this thesis.

Research study design

With respect to the research design, there are several changes and considerations that the pandemic influenced.

The original study design included data collection at 4 points, each separated by approximately 6 months. Due to the national lock down, I was unable to collect data point 4 at the planned point leading to a gap of 12 months between sets 3 and 4. This is an important consideration in study design. It has previously been identified that to capture meaningful associations between screening variables and injury, frequent sampling is required (Bittencourt et al., 2016; Stern et al., 2020). Any fluctuations in data would not have been detected during this period and therefore sensitivity of the screening tool is likely to be reduced.

In attempt to minimise the risk of spread of infection and mitigate the threat of Covid-19, the methodology for assessment was reviewed and altered based on need and risk analysis. Consequently, preliminary data analysis was conducted, and the method was adapted. Assessments were only carried out if analysis of time points 1 to 3 showed discernible differences between groups. The Y-balance test and single-leg squat were not carried out and only sagittal views of the double-leg squat were performed to minimise athlete contact time. Heightened infection control procedures were practiced by both researcher and participants in accordance with guidance provided by the English Institute of Sport. Personal protective equipment (PPE) was worn at all times by the researcher and the study participants wore medical grade face masks. Informed, verbal consent was obtained for each participant to ensure they remained happy to participate and they were reminded that they were able to withdraw from the process at any stage.

Confounding factors

There is a substantial amount of research investigating the positive and negative association between training load, injury and performance (Gabbett, 2020). An assumption of this thesis has been the standardisation of the training programme. Participants were all members of the national rowing squad, completing the national training programme. Therefore, training load in this study was assumed to be a constant.

The secondary influencers on this research were: the consequences of a national lockdown, and the 12-month delay to the Olympic Games. The impact of these events was three-fold: (1) The delay in Olympic Games led to a change in the training programme resulting in a second period of winter-style endurance training with an associated increase in external training load. (2) Environmental constraints also led to a change in training modalities. Typically, approximately 75% of an elite rowers training is completed on the water. During this time a significant amount of training was completed on the rowing ergometer, in itself this is known to be associated with increased risk of injury due to higher loading (Wilson et al., 2014). (3) Varying personal circumstances during the six-month lockdown period meant adherence to the programme was mixed and, where training was done, application of the programme (i.e., training modality used: ergo, road bike, running etc..) was varied. This introduces more variables when looking at this data set. The impact of these factors on the research findings are unknown at this stage.

CHAPTER 1

1 INTRODUCTION

“There's no earthly way of knowing
Which direction they are going!
There's no knowing where they're rowing,
Or which way the river's flowing!
Not a speck of light is showing,
So the danger must be growing,
For the rowers keep on rowing,
And they're certainly not showing
Any signs that they are slowing. . . .”

Roald Dahl, Charlie and the Chocolate Factory

1.1 Rowing

Rowing is a strength-endurance sport, which is considered to be one of the most physically demanding (Hagerman, 1984). A complex interaction of outstanding physiological qualities (Hagerman, 1984) and technique (Maestu et al., 2005), utilising almost all muscles in the body, is required to propel the boat through the water (Secher, 2000). It is one of Great Britain and Northern Irelands’ most successful Olympic sports, winning a total of 70 medals, up to and including Tokyo 2021 (British Rowing, 2021). In 2020, it was reported that around 574 thousand people in the United Kingdom were participating in rowing (Lang, 2020).

Rowing is one of only five sports that have been included in every modern Olympic Games, starting with men in 1900, followed by the introduction of women's events in 1976. Olympic events are raced over a 2,000m course taking between 5 and a half to 7 minutes depending on the boat class, and completing between 32-38 strokes per minute to cover the distance (Maestu et al., 2005). There are 14 Olympic boat classes which are made up of two distinct disciplines: sculling and sweep rowing. When sculling, rowers use two oars per person performing a symmetrical stroke. During sweep rowing, rowers use one oar per person, rotating to either the left (starboard, bow side) or right (port, stroke side). Figure 1-1 illustrates the different boat classes in sculling and sweep oar rowing. Rowers are further categorised as either open weight or lightweight; women competing individually below 57kg with a crew average of <59kg, men, individually <72kg with a crew average <70kg. Since 2005, rowing has also been included in the Paralympic games with a further 5 boat classes.

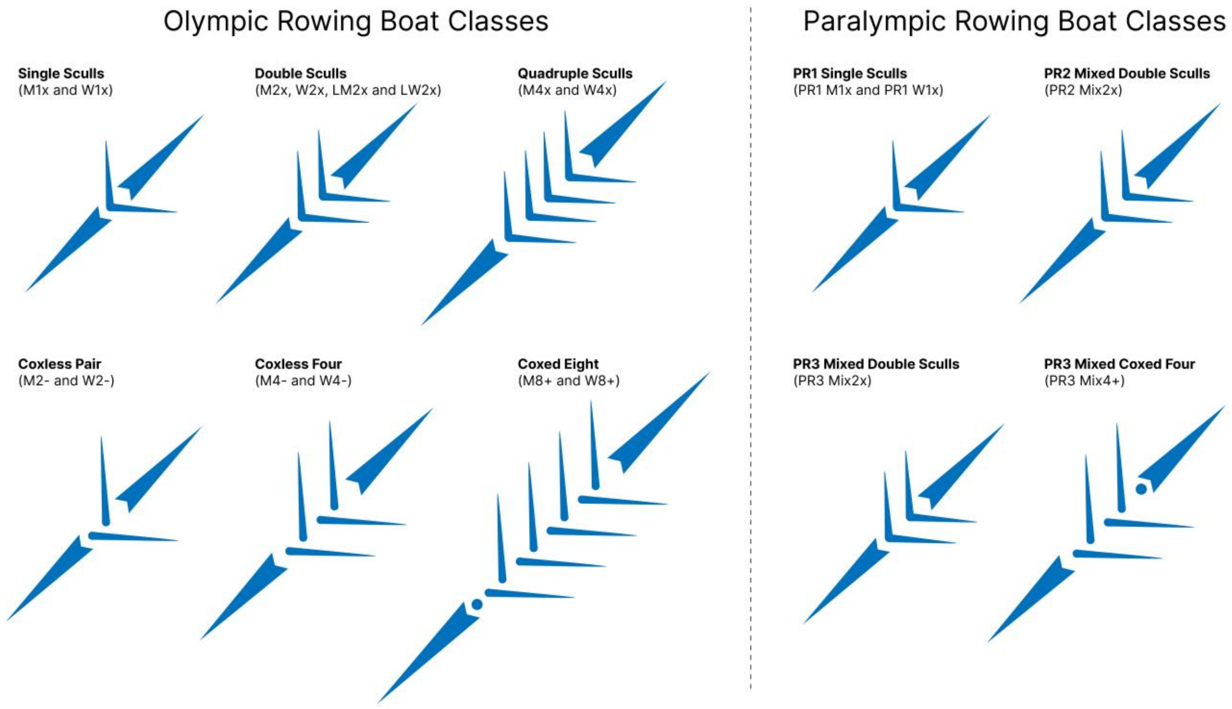


Figure 1-1: Olympic and Paralympic Boat Classes (Source: https://madebyjess.co.uk)

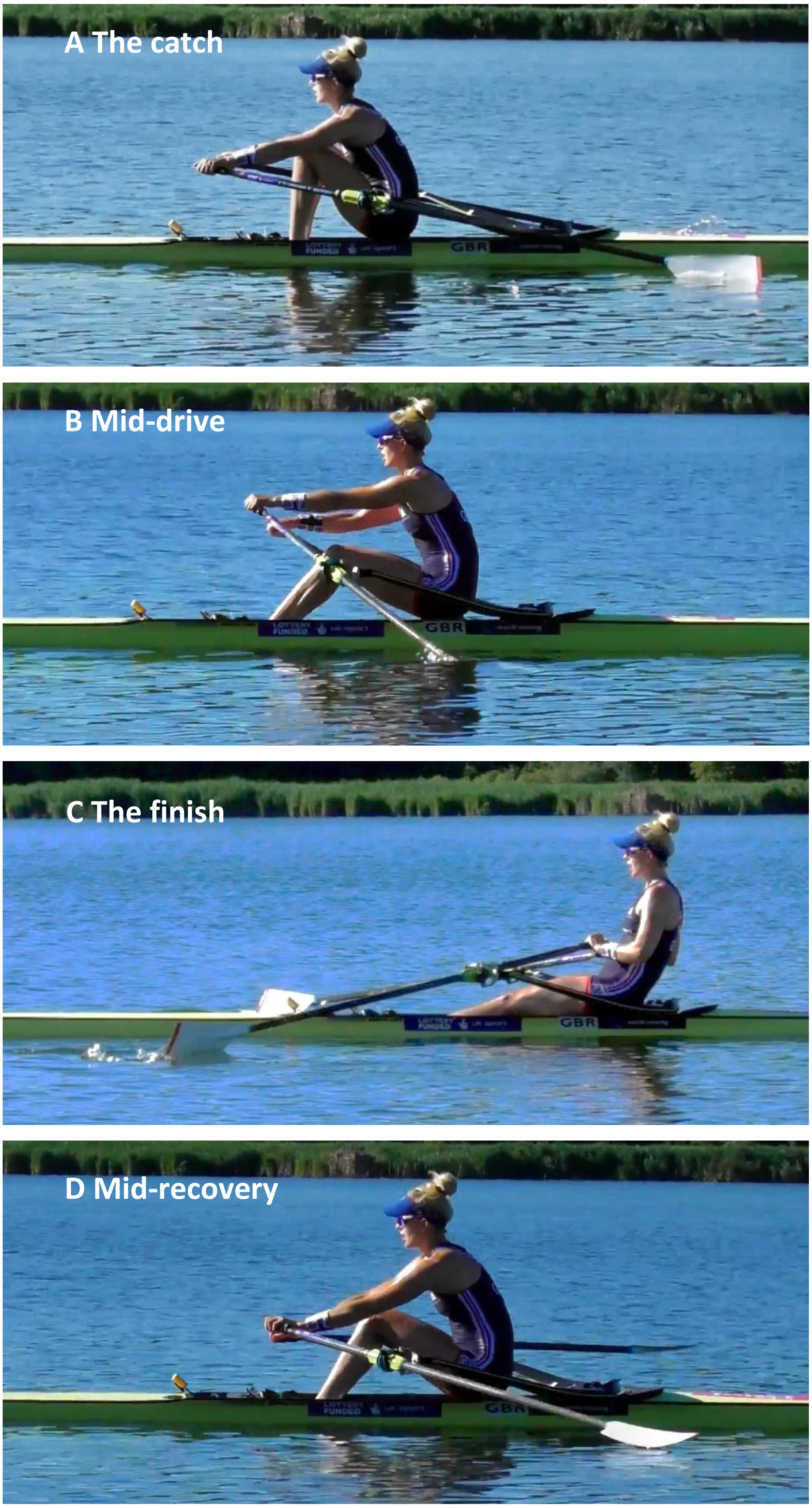


Figure 1-2: The rowing stroke. (Images used with athlete consent)

1.1.1 The rowing stroke

The rowing stroke is a continuous cyclical process, divided into two distinct phases: the *drive*, and the *recovery.*

The start of the *drive* phase is identified by the *catch* position (Figure 1-2A): the lower body is compressed, the hips and knees flexed, the shins vertical, and the trunk rotated anteriorly at the pelvis, the arms are extended. As the blade enters the water, the *drive* phase (Figure 1-2B) is initiated through powerful extension of the legs (McArthur, 1997). The trunk then begins to accelerate backwards through a ‘back-opening’ motion generated by extension of the hips (Redgrave, 1997). To accelerate the boat, the trunk and pelvis transmit force generated through the legs, to the blade (Holt et al., 2003a). The *drive* phase is completed as the elbows flex, drawing the blade-handle through to the chest and the extraction of the blade from the water. This signifies the *finish* position (Figure 1-2C) and the point at which the *recovery* phase begins (Figure 1-2D).

The *recovery* phase is essentially the reverse of the *drive* phase. The arms extend until they are straight, the body pivots over through hips and the lower limbs begin to flex as the rower slides forwards in preparation for the catch (McArthur, 1997). Precision of these movements, in conjunction with accurate hand skills, is important to maximise boat velocity (Caplan et al., 2010).

1.1.2 Determinants of rowing performance

Anthropometry in rowers has been extensively studied (Bourgois J et al., 2001; Bourgois et al., 2000; Jürimäe et al., 2000; Kerr et al., 2007; Russell et al., 1998). Mikulic (2008) found that elite rowers were taller, and heavier with longer limbs than their sub-elite counterparts. The characteristics described above allow for long strokes, which are associated with more successful rowing performances (Ingham et al., 2002), as taller rowers are placed at a mechanical advantage if they are able to efficeintly optimise limb length (Bourgois et al., 2000).

The key physiological determinants of rowing performance have been investigated comprehensively identifing some key factors. Maximal aerobic power ($\dot{V}O_{2max}$) is widely reported as the strongest predictor of both 2000m ergometer (Cosgrove et al., 1999; Kramer et al., 1994) and on-water performance (Secher et al., 1982). Sub-maximal markers of aerobic capacity such as the power produced at 2 and 4 mmol·l-1 of lactate during incremental tests are often used, and correlate highly with ergometer performance (Steinacker, 1993; Steinacker et al., 1998).

Strength and power have also been identified as a key factor in determining boat efficiency (Baudouin & Hawkins, 2002; Gee et al., 2011; Maestu et al., 2005). The average power generated during an international race can range between 450-550 W, with peak power per stroke reaching up to 1200 W (Steinacker, 1993). A large proportion of this power comes from the legs (46.4%), then the trunk (30.9%) and upper body respectively (22.7%) (Kleshnev, 2000). Leg strength generates forces directly onto the foot stretcher, while the whole human system operates as the mechanical link between the foot stretcher and the force produced at the handle (Baudouin & Hawkins, 2002). Leg strength in particular has been shown to significantly correlate with 2,000m ergo performance (Russell et al., 1998; Yoshiga & Higuchi, 2003). This places a large demand on the development of effective leg strength in conjunction with appropriately developed trunk and upper body musculature to transmit force to the blade handle (Tonks, 2005).

High volumes of endurance training, whether quantified as training time or mileage, are believed to be one of the foundations of successful performance in elite rowing (Maestu et al., 2005). Elite rowers typically complete between 11-16 training sessions per week (Arne et al., 2009; Mikulic, 2011; Tran et al., 2015) with 2-3 session per week devoted to strength training during the non-competitive season (Gee et al., 2011; Secher, 1993). In elite Norwegian rowers, approximately 80% of training time is described as 'low intensity' aerobic training (below lactate threshold) and the remaining 20% completed at higher intensities (Fiskerstrand & Seiler, 2004). This type of training intensity distribution has been described as 'Polarized' (Seiler, 2010). These typical training regimes reflect the energy system requirements of a 2000m rowing race (Ingham et al., 2002). The aerobic and anaerobic energy contributions on a 2000m rowing race have been reported as 70-86% and 14-30%, respectively (Hagerman et al., 1978; Secher et al., 1982).

1.2 Low back pain in rowing

Compared to many sports, injury risk in rowing is relatively low (Engebretsen et al., 2013). When injuries do occur, they are most commonly overuse in nature (Smoljanovic et al., 2015). The low back is the most commonly injured site in rowers (Hickey et al., 1997; Rumball et al., 2005; Trease et al., 2020; Wilson et al., 2010) and is characterised as *a symptom that can result from several different known or unknown abnormalities* (Wilson et al., 2021).

Injury epidemiology research within rowing is typically retrospective, cross-sectional or case series in design (Newlands et al., 2015) yet the theme of low back pain (LBP) remains constant. Two prospective studies have identified the magnitude of LBP in elite rowers. Wilson et al., (2010) reported 32% of all injuries reported in a cohort of 20 international Irish rowers were related to the lumbar spine. Trease et al., (2020) found that LBP accounted for 21% of all injury and illness reported over two Olympic cycles in Australian rowers. This supports previous findings that have indicated the low back as most common site of injury in international (Newlands et al., 2015; Smoljanovic et al., 2015), college (Hosea & Hannafin, 2012; Teitz et al., 2002) and junior rowers (Smoljanovic et al., 2009) as well as amateur club rowers (Finlay et al., 2020).

Incidence of low back pain has been reported as between 1.67 (Newlands et al., 2015) and 3.67 (Wilson et al., 2020) episodes per 1000 hours of rowing, although just ~10% of these injuries are deemed ‘significant’, as indicated by time lost from training (Newlands et al., 2015; Smoljanovic et al., 2015). Data from injury observation studies should be interpreted with some degree of caution as it is not clear if injuries were recurrent events, reinjuries or exacerbations.

During the rowing stroke, the spine serves as a key component of the kinetic chain, transferring power generated by the legs to the oar (Holt et al., 2003a). The *drive* phase subjects the lumbar spine to extreme compression forces with peak loading reported in excess of 6000N and 5000N and anterior shear forces reaching 848N and 717N, for males and females, respectively (Reid & McNair, 2000). Rowers have been shown to achieve relatively high levels of lumbar spine flexion during the rowing stroke, which increases with time and fatigue (Caldwell et al., 2003; Holt et al., 2003b) and is exacerbated on the static rowing ergometer (indoor) (Wilson et al., 2013). McGregor et al., (2002) found rowers with existing LBP demonstrated greater posterior pelvic rotation at both the catch and the finish, further supporting this theory, however study participant numbers were small (n=9) and causation cannot be assumed. These mechanisms of high force in lumbar flexion, in association with the high cyclical loading seen during training sessions and racing, have been identified as potential mechanisms for injuries to the spinal tissues (Coenen et al., 2014; Gallagher et al., 2005).

Key risk factors have been identified for LBP in the rowing population, including; previous injury (Newlands et al., 2015; O'Kane et al., 2003; Wilson et al., 2014), high training volume (Newlands et al., 2015; Smoljanovic et al., 2015; Wilson et al., 2014) and high ergometer training volume (Wilson et al., 2014). During winter months, ergometer training volume is often elevated due to gusting winds, frozen lakes and fast flowing rivers. As high training volumes are commonly reported as a necessary component of successful rowing performance (Fiskerstrand & Seiler, 2004; Mikulic, 2011), finding alternative ways to identify and manage injury risks are imperative.

1.3 The role of the hip in rowing

Hip and/or groin injuries in international rowers account for 2.8-8.4% of all reported injuries (Smoljanovic et al., 2009; Trease et al., 2020). Despite the relatively low reported incidence and prevalence of hip problems, it is hypothesised that hip function may play a greater role in the health of a rower.

The 2021 consensus statement for prevention and management of LBP in rowers identified reduced hip range of movement as a potential risk factor (Wilson et al., 2021). It is suggested that reduced hip flexion and/or internal rotation, may be a causative factor in the development of LBP in rowers and/or contribute to time loss from training. The complex relationship between hip and spine pain was first documented by Offierski & MacNab (1983), and recently with respect to femoroacetabular impingement syndrome (Brown-Taylor et al., 2021; Rivière et al., 2017), yet literature on this topic in relation to the athletic population is limited.

Figure 1-3: The rowing hip.
(Image used with athlete consent. Source: https://madebyjess.co.uk)

Two recent observational studies found evidence of hip pathology in asymptomatic elite male and female rowers. Bittersohl et al., (2019) used MRI to show a greater degree of cartilage degeneration, both femoral and acetabular, in elite rowers when compared with asymptomatic controls. While Wedatilake (2021) reported 85% of rowers had cam morphology in at least one hip, 60% had bilateral involvement and 95% had acetabular labral tears. Unlike the former study, only one hip had evidence of pathological changes to the articular cartilage. Hip joint IR and size of cam morphology have also been correlated with presence of degenerative lumbar spine disc disease in elite rowers (Wedatilake et al., 2021). As cam morphology has been suggested as a precursor to the development of hip joint osteoarthritis (Ganz et al., 2003), it is therefore an important consideration for the long-term health of the elite rowing population.

In the presence of cam morphology, two mechanisms are proposed (Figure 1-4): (1) repeated hyperflexion, as seen during the rowing stroke, may lead to the development of a symptomatic hip joint due to premature contact between the proximal femur and acetabulum (Boykin et al., 2013), (2) restriction in hip range may result in posterior rotation of the pelvis coming into the catch position. Increased posterior pelvic rotation at both the catch and finish positions have previously been identified in rowers with existing LBP symptoms (McGregor et al., 2002; Nugent et al., 2021). Asymmetries in hip range of movement (Buckeridge et al., 2012), as well as smaller ranges of hip flexion (Buckeridge et al., 2015) have also been shown to correlate with increasing ranges of lumbar-pelvic flexion through the rowing stroke.

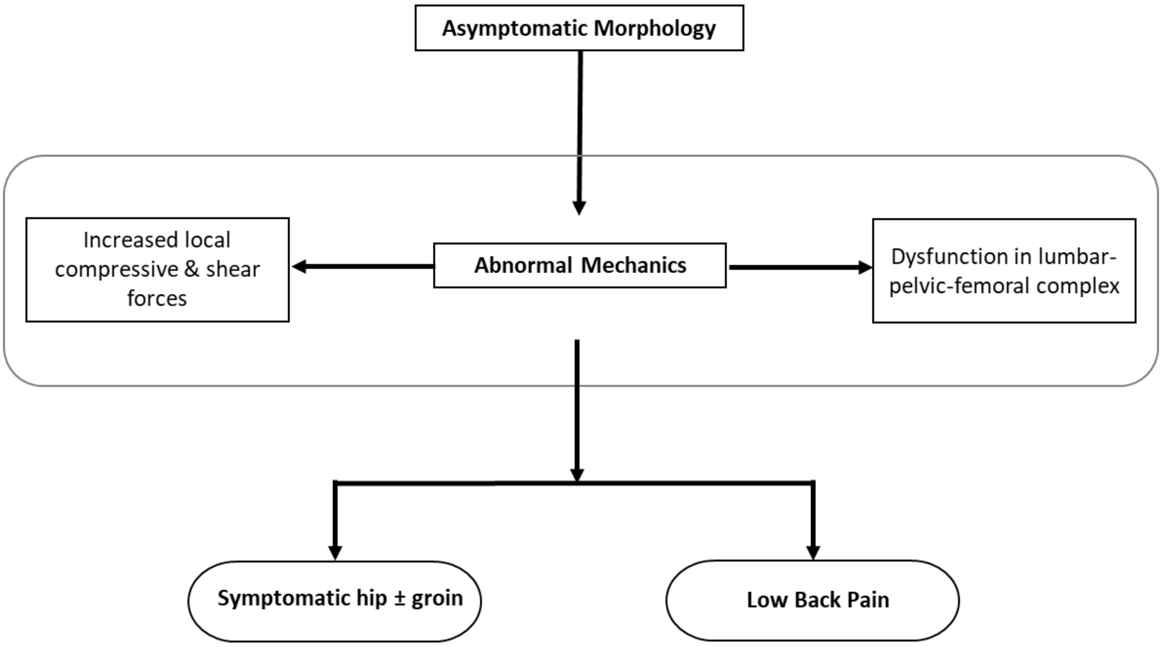


Figure 1-4: Theoretical framework showing proposed mechanism of hip or back pain in the presence of cam morphology.

The role of hip motion in relation to rowing performance has been well documented due to the work generated at Imperial College, London. The research group found that total hip range of motion achieved during the rowing stroke increases with experience with healthy elite rowers demonstrating significantly greater ranges than those seen in novice rowers

(Buckeridge et al., 2012). Not only are greater ranges associated with smaller lumbar flexion angles at the catch, but greater angles of hip flexion during key phases of the rowing stroke, have been identified as a key component in generating large resultant foot forces (Buckeridge et al., 2015). Maintaining high degrees of hip flexion during the initial drive phase, enables the rower to maintain the desirable postural position (Soper & Hume, 2004) in order to generate optimal force production through the legs (Buckeridge, 2013). This has been identified as a key biomechanical determinant of rowing performance (Buckeridge et al., 2015).

The role of the hip joint in an elite rower affects the key biomechanical determinants of performance, an athlete's ability to tolerate a high-volume training programme, and both short- and long-term health. These factors make the hip a key area for consideration for coaches, sports medicine practitioners, and sports scientists, alike. Gaining greater insight into the determinants of hip health in rowers, may subsequently add to the body of knowledge concerning LBP in the rowing population.

1.4 Hip-related pain

Hip and groin pain in an athlete is common and complex. In 2014, the 'Doha agreement meeting on terminology and definitions in groin pain in athletes' simplified and standardised terminology to aid clinical practice and research (Weir et al., 2015). This led to a 3-point classification system which included hip-related pain (HRP). This can be further divided into: (1) femoroacetabular impingement syndrome (FAIS), (2) acetabular dysplasia and/or hip instability and (3) other conditions causing hip-related pain without specific bony morphology, such as labral, chondral and/or ligamentum teres conditions (Reiman et al., 2020). Due to the work conducted by Bittersohl (2019) and Wedatilake (2021) in rowers, the following sections will focus more specifically on FAIS. (See Figure 1-5).

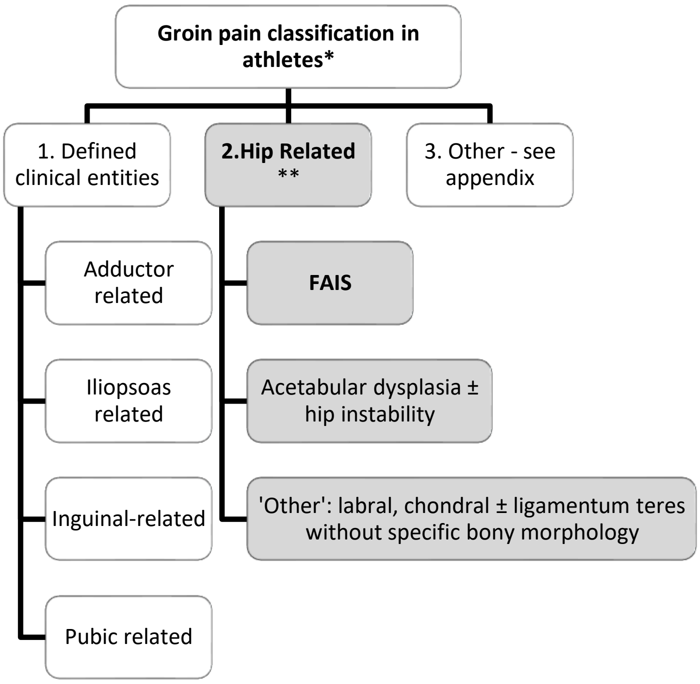


Figure 1-5: Groin pain classification

**taken from 'Doha agreement meeting on terminology and definitions in groin pain in athlete' Weir et al., 2015. **taken from the 'Consensus recommendations on the classification, definition and diagnostic criteria of hip-related pain in young and middle-aged active adults from the International Hip-related Pain Research Network, Zurich 2018' Reiman et al., (2020).*

1.5 Femoroacetabular Impingement Syndrome (FAIS)

Femoroacetabular impingement (FAI) was first described by Ganz et al. (2003) as a motion-related disorder proposed as a mechanism for the development of osteoarthritis (OA) of the hip joint. More recently, the term FAIS has been used to describe a condition which presents with a triad of symptoms, clinical signs and imaging findings that occur because of premature contact between the proximal femur and the acetabulum (Griffin et al., 2016). It is this abnormal contact which can lead to the development of chondrolabral pathology, which has become associated with FAIS. There are three main types of morphology which may constitute FAIS: cam, pincer, and those with mixed cam-pincer morphology (Cheatham, Enseki, & Kolber, 2016). Cam morphology describes extra bone formation in the antero-lateral femoral head-neck junction (Rintje Agricola et al., 2013) whereas pincer morphology is characterised by over-coverage of the acetabulum relative to the femoral head (R. Agricola et al., 2013). More recently, it has also been acknowledged that femoral and acetabular versions can contribute to the development of hip pain in those with FAI-morphology (Lerch et al., 2018).

The prevalence of cam-type FAI-morphology is reported to be 15-75% (Dickenson et al., 2016; Hack, Di Primio, Rakhra, & Beaulé, 2010), with an almost three-times increase in prevalence, when considering the athletic population in isolation verses the non-athletic (Frank et al., 2015). Primary cam morphology develops during skeletal maturation in young adolescents as a consequence of high exposures to athletic activities, whereas secondary cam morphology develops due to existing hip disease or trauma, including Perthes disease, slipped capital femoral epiphysis, healed proximal femoral fractures or acute fracture (Dijkstra et al., 2023). A correlation has been shown between large cam deformities, restriction of motion and progression to OA (Agricola et al., 2013), however, many hips with cam-morphology will remain asymptomatic (Agricola & Weinans, 2016). In recent years there has become a growing interest in understanding why some individuals with underlying morphology develop the clinical signs and symptoms of FAIS and others do not (Agricola et al., 2014; Hack et al., 2010; Ng et al., 2016) but at present, this remains unknown (Griffin et al, 2016). It is possible that the cause of pain and pathology in this group is a consequence of a multitude of factors. Impingement sports such as rowing and ice hockey, which require a high frequency of hyperflexion (Doran et al., 2021), in conjunction with aberrant hip and pelvic kinematics, predispose individuals to the development of pathomechanics and FAIS (Bagwell et al., 2016b).

There has been a substantial increase in hip-joint preserving surgery for FAIS over the past 10 years (Truntzer et al., 2017), with FAIS accounting for the most common cause of hip and groin pain that requires surgical intervention in the athletic population (de Sa et al., 2016). The ‘return to sport’ rate in both professional and recreational sports, more than 2 years post-surgery, is 87% (Casartelli, Leunig, Maffiuletti, & Bizzini, 2015). However, only ~43% are believed to return to the same level of competition or performance (Ishøi et al., 2018). With a sub-optimal return to athletic performance level, and a known increase in comorbidities following hip arthroscopy (Rhon, Greenlee, Marchant, Sissel, & Cook, 2018), it would be pertinent to gain greater clarity on the causality of FAIS to ensure best decisions are made with respect to its prediction, prevention, and management.

1.6 Risk-factors & Musculoskeletal Screening

It is widely accepted that injury risk is complex, non-linear, and multifactorial (Bittencourt et al., 2016; Meeuwisse et al., 2007), and therefore a deterministic model of injury requires an understanding of all potential causative factors, as well as the interactions between them (Bittencourt et al., 2016). To develop appropriate injury mitigation strategies, it is necessary to understand the contributing risk factors and injury mechanisms within the target population, which may contribute to making an individual more susceptible (Finch, 2006; van Mechelen et al., 1992).

Risk factors are defined as exposures that are causally associated with an outcome (Riley et al., 2019). These are commonly divided into two categories: intrinsic factors (person specific), which predispose an athlete, and extrinsic factors (environment specific), interactions which may lead to an injury susceptible athlete (Figure 1-6) (Meeuwisse et al., 2007). These can be further classified into modifiable (e.g., strength, flexibility, neuromuscular control) and non-modifiable factors (e.g., age, sex).

Periodic health examination practices, which include musculoskeletal screening, are commonplace in elite sport with the aim detecting current health problems and identifying individuals at risk of future problems (Ljungqvist et al., 2009). Screening assessments are used to inform risk mitigation strategies and are often targeted towards modifiable risk-factors, as these may be influenced by intervention programmes (Bahr, 2016).

Bahr (2016) recently outlined the necessary steps required to validate a screening protocol. This starts with the clear identification of risk factors and relevant thresholds which should be achieved via prospective cohort studies. Without this information, injury prediction cannot be validated (Bahr, 2016) nor prevention strategies be instigated (Finch, 2006; Bahr 2016). This has consequences for both research and clinical practice alike.

To the authors knowledge, no study has explored the intrinsic risk factors associated with HRP in an elite rowing population. Therefore, the aim of this research is to sequentially explore the association between intrinsic risk factors and HRP in a cohort of elite rowers with a view to informing future screening and injury prevention research and practices of the Great Britain Rowing Team.

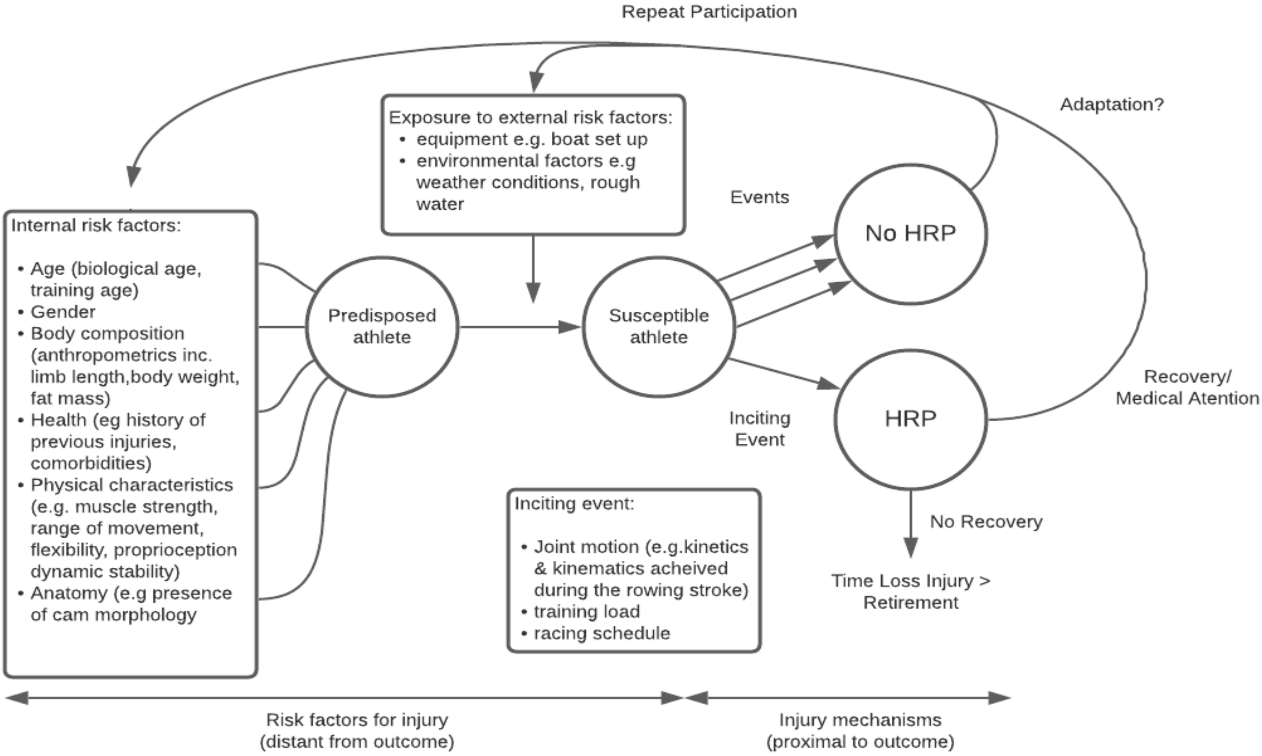


Figure 1-6: A multifactorial model of rowing injury aetiology, adapted from Bahr & Holme (2003) and Meeuwisse (2007).

1.7 Aims

The primary aim of this thesis is to investigate the association between intrinsic risk factors and hip-related pain (HRP) in a cohort of elite rowers.

Furthermore, the thesis aims to advance the understanding of HRP in elite rowers to inform the future screening and injury prevention practices.

1.8 Objectives

The thesis aims will be met through the following objectives:

1. Determine the accuracy of clinical assessment in the diagnosis of FAIS and acetabular labral tears.
2. Identify physical and biomechanical presentations of individuals with FAIS.
3. Establish the reliability of a battery of screening assessments to be used in the experimental chapters.
4. Examine the differences in screening profiles between rowers with and without a history of HRP.
5. Identify intrinsic risk factors for HRP in elite rowers via a prospective cohort study.
6. Explore the impact of an exercise-based intervention on intrinsic risk factors for HRP.

This is further outlined in figure 1.7 and section 1.9.

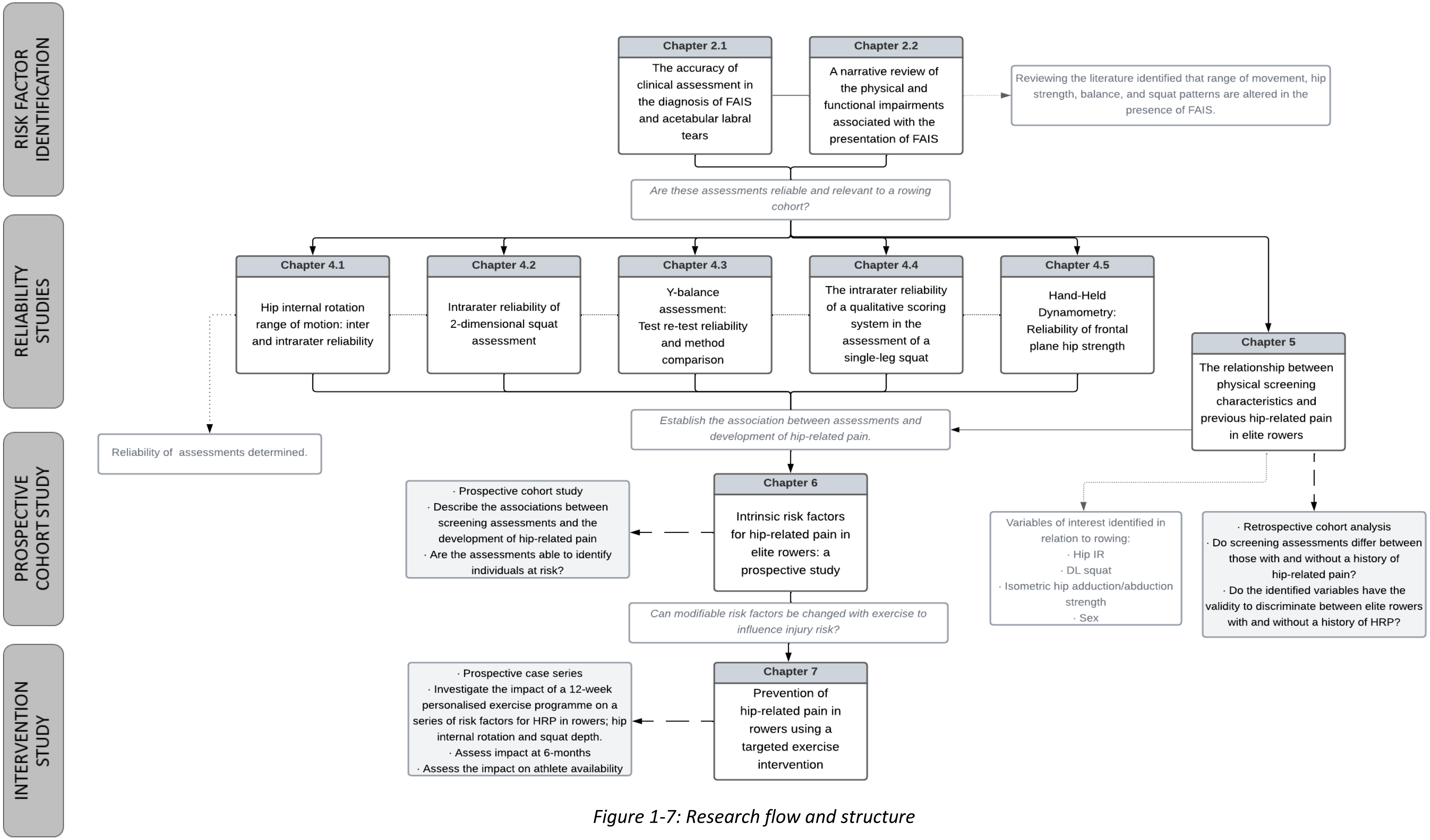


Figure 1-7: Research flow and structure

1.9 Research Overview

The thesis will be presented in the following chapters:

- **Chapter 1** introduces the reader to the sport of rowing and the role of the hip in relation to the rowing stroke. The chapter will highlight the relevance and novelty of considering hip health in elite rowing and touches on current philosophies around the specific condition of FAIS.
- **Chapter 2** reviews the current literature on the topic of HRP. The chapter will explore the accuracy of clinical diagnostics as well as the physical presentations and biomechanical variables of those experiencing FAIS. This chapter is used to identify the variables that will be taken forward to the experimental studies.
- **Chapter 3** describes the general methods used throughout all the experimental chapters.
- **Chapter 4** determines the reliability of the five assessments that will be used in the experimental studies.
- **Chapter 5** is a retrospective cohort study which examines the differences in screening profiles between rowers with and without a history of HRP. This chapter also ascertains whether assessments have the validity to discriminate between elite rowers with and without a history of HRP.
- **Chapter 6** is a prospective study which investigates the differences in screening characteristics between rowers who do, and do not, go on to develop HRP. It also establishes the association between risk factors and the development of HRP, with and without time-loss injuries, due to HRP.
- **Chapter 7** uses the risk factors identified in Chapter 6 to repeat the screening in a new cohort of rowers. The impact of an exercise-based intervention is then explored on those individuals identified as being at higher risk of developing HRP.
- **Chapter 8** provides an overall discussion and summary of the work done and makes recommendations for future research.

CHAPTER 2

2 REVIEW OF LITERATURE

2.1 Introduction

To identify risk factors for hip-related pain (HRP) in elite rowers, it is important to understand what is currently known on the topic in relation to other demographics. This is due to the dearth of literature specifically in rowing. This information will be used to inform the development of the methodology in the forthcoming chapters.

Chapter 2 will focus specifically on femoroacetabular impingement syndrome (FAIS), a subclassification of HRP (Figure 1-5), as recent literature identifies high levels of these specific intra-articular hip pathologies in the elite rowing population, with no mention of acetabular dysplasia and/or instability (Bittersohl et al., 2019; Wedatilake et al., 2021).

This chapter will initially present an up-to-date review of the literature looking at the utility of clinical assessments for the diagnosis of FAIS and/or acetabular labral tears (ALT). This is to understand the accuracy of tests and to establish whether diagnostic assessments have the potential to contribute to, and/or guide the development of a screening proforma. The second half of the chapter aims to explore the physical and biomechanical characteristics of those with FAIS and/or ALT. The findings of this chapter will be used to identify potential factors which will to be taken forward to inform the experimental work undertaken in this thesis.

2.2 The accuracy of clinical assessment in the diagnosis of FAIS and acetabular labral tears

As defined in the Warwick consensus, physical examination is a key component in the diagnosis of FAIS (Griffin et al., 2016). To date, the literature surrounding clinical diagnostic tests has been inconclusive with limited high-quality studies available to adequately influence clinical practice (Reiman et al., 2015; Reiman et al., 2013; Tijssen et al., 2012). The aim of the first section is to conduct an up-to-date literature review to determine the accuracy of clinical assessment in the diagnosis of FAIS and ALT.

2.2.1 Methods

2.2.1.1 *Search strategy*

The literature review was developed in accordance with the *Cochrane Handbook for Systematic Reviews of Diagnostic Test Accurac*y (de Vet, Riphagen & Aertgeerts, 2008). The *Preferred Reporting Items for Systematic Review and Meta-Analyses* (PRISMA) checklist (Moher et al., 2009) was also utilised to guide the process in order to optimise the quality of the review. A search was conducted using the electronic databases, MEDLINE, EMBASE and CINHAL. Further articles were retrieved by screening reference lists and citation searches of identified literature (Greenhalgh & Peacock, 2005) and through following relevant researchers and journals on social media. The search was confined to January 2000 to September 2018 as this coincided with a growing interest in FAI at the start of the millennium (Griffin et al., 2016). The electronic searches were conducted by combining the following terms: *IAHP, groin pain, hip pain, hip impingement, femoroacetabular impingement, FAI, FAIS, labral tear, acetabular labral tear, early OA, hip injury, Cam, Cam morphology, pincer, pincer morphology, diagnos**, assess*, clinical, radio*, FADDIR, FADIR, FABER, internal rotation, strength, range of motion, range of movement.*

2.2.1.2 *Inclusion/exclusion criteria*

Article titles and abstracts were screened by the lead author (E.J.A) using the following inclusion criteria: (1) written in English language; (2) any study design; (3) included one or more diagnostic index tests for FAI, ALT, or other intra-articular hip pathology; (4) readily available statistical data. Studies were excluded according to the following criteria: (1) extra-articular hip pathology; (2) referred pain into the hip/groin from another source e.g., lumbar spine.

2.2.1.3 *Quality Assessment*

Papers identified were assessed using the *Quality Assessment of Diagnostic Accuracy Studies (QUADAS-2)* tool. QUADAS-2 has been developed to be able to more accurately assess (Martin et al., 2008) and rate the bias and applicability of primary diagnostic studies (Whiting et al., 2011). All papers were reviewed by the author (E.J.A); a summary is presented in Table 2-1.

Table 2-1: Primary Purpose(s) & QUADAS assessment of included studies

Study	Data Collection	Primary Purpose of Study	Risk of Bias				Applicability Concerns		
			Patient Selection	Index Test	Reference Standard	Flow & Timing	Patient Selection	Index Test	Reference Standard
Ayeni et al. (2014)	Unclear	Diagnostic utility of maximal squat test for the presence of Cam type deformity	Low	Low	High	Unclear	Low	Low	High
Casartelli et al., (2018)	Prospective	Diagnostic accuracy of FADDIR for screening FAI morphology in youth ice hockey players	Low	Low	Low	Low	Low	Low	Low
Hananouchi et al., (2012)	Prospective	Diagnostic accuracy of FADDIR test in 4 patient groups	High	Low	High	Low	Low	Low	High
Kapron et al., (2012)	Prospective	Diagnostic accuracy of clinical tests in the detection of FAI in college football players	High	Low	High	Low	Low	High	High

Laborie et al., (2013)	Prospective	Prevalence of a positive impingement test in healthy individuals	High	Low	High	Unclear	Low	High	High
Martin et al., (2008)	Prospective	Diagnostic accuracy of clinical tests	High	Low	Unclear	High	High	Low	Unclear
Mayes et al., (2016)	Retrospective	Prevalence of ALT in ballet dancers compared with sporting participants	Unclear	Low	Low	Unclear	Low	Low	Low
Murphy et al., (2017)	Retrospective	Determine the correlation between Hip IR ROM and Cam	Low	Low	Low	Low	High	Low	High
Myrick & Nissen (2013)	Retrospective	Diagnostic accuracy of THIRD test in ALT	High	High	High	High	High	High	High
Narvani et al., (2003)	Prospective	Prevalence of ALT in sports patients with groin pain	High	High	Unclear	High	Low	Low	Low

Nogier et al., (2010)	Prospective	Epidemiology of patients with mechanical hip pain	Low	Low	High	Low	Low	High	High
Sink et al., (2008)	Retrospective	Clinical Presentation of FAI in adolescent athletic hips	High	Low	High	Low	Low	Unclear	High
Tijssen et al., (2017)	Retrospective	Investigate the relationship between patient history, clinical examination, and arthroscopy findings	High	Low	Low	Low	Low	Low	Low
Trindade et al., (2018)	Prospective	Determine diagnostic value of FDT in the diagnosis of cam-type FAI	High	Low	Low	Low	Low	Low	Low
Troelsen et al., (2009)	Prospective	Diagnostic accuracy of clinical tests and US compared to MRA in patients who have had periarticular osteotomies	High	Low	Low	Unclear	High	Low	Low
Wang et al., (2011)	Retrospective	Diagnostic accuracy of clinical tests compared to arthroscopic outcomes	High	Unclear	Unclear	Unclear	High	Low	High

ALT, acetabular labral tear; FADDIR, flexion-adduction-internal rotation impingement test; FAI, femoroacetabular impingement; IR, internal rotation; MRA, MR arthrogram; ROM, range of movement; THIRD, the Hip IR with distraction test; US, Ultrasound.

Table 2-2: Demographics and characteristics of included studies

Study	Participants: n, age, sex, symptoms duration	Pathology	Reference Standard	Clinical Test Investigated
Ayeni et al., (2014)	76 participants (78 hips), mean age 38.3years, 39 females, NR	Cam-FAI, various other pathology	MRI or MRA 1.5Teslar; α > 55° ± loss of femoral head-neck offset <9.0mm	• Squat
Casartelli et al., (2018)	74 male youth ice hockey players, mean age 16 years (13-20)	Cam/Pincer/Combo or Cam/Combo with AL alterations	MRI, 1.5Teslar; α > 60°, acetabular retroversion ± acetabular depth ≤3mm	• FADDIR
Hananouchi et al., (2012)	69 participants, (107 hips), mean age 57.2 years (27-81 years), NR	FAI, Dysplasia, ALT	MRI 3T; FAI crossover sign, α > 50°, aspherical femoral head, or CEA >40° Dysplasia: CEA <25°	• FADDIR

Kapron et al., (2012)	65 male college football players, mean age 21 ± 1.9years, 'most' asymptomatic at time of study (ADLs and sports sub-scores 99%±3.9% and 98% ± 4.4%)	FAI	AP & Frog-lateral radiograph; α >50°, head-neck offset <8mm, lateral CEA >40°, acetabular index <0°, cross-over sign	• FABER • FADDIR • ROM
Laborie et al (2013)	1170 participants, 19 years, 672 females,	FAI	AP & frog-leg view radiographs; CEA 45°, α angle males ≥83°, females ≥57°, triangular index, posterior-wall sign, cross-over sign, visual inspection for pistol grip deformity, focal prominence of femoral head, lateral flattening of femora neck	• FADDIR
Martin et al., (2008)	105 participants, mean age 42±15years (18-68yrs), 24 females' potential surgical candidates, 1.9yrs	ALT, FAI, arthritic changes	Intra-articular Injection with < or > 50% pain relief	• FADDIR • FABER • Trochanteric palpation
Maslowski et al., (2010)	50 participants, mean age 60.2±13 years, 30 females, NR	Various IAHP	Intra-articular Injection ≥80% pain relief	• FABER • Resisted SLR • Scour test • IROP
Mayes et al., (2016)	98 participants (98 hips): 49 professional ballet dancers (current and retired), mean age 30years (19-64), 28 females, 49 (98 hips) age-matched, sex-matched sporting participants	ALT, cartilage	MRI 3.0 Tesla	• IR at 90° flexion

Murphy et al., (2017)	21 participants (42 hips) male semi-elite Australian Football players, average age 21.1±2.5yrs, athletes with and without hip/groin pain, symptoms duration not reported	Cam-FAI	90° Dunn view radiograph, $\alpha > 60°$,	- Flexion-IR test - Modified Maximum Squat
Myrick & Nissen (2013)	100 participants, age 10-40 years, sex not reported, NR	ALT	Arthroscopy	- THIRD
Narvani et al (2003)	18 participants with groin pain, mean age 30.5±8.5years, 5 females, NR	ALT	MRA 1.0T	- Flexion-IR plus Compression - Thomas test
Nogier et al., (2010)	292 participants with mechanical hip pain, mean age 35±10years, 111 females, mean duration of symptoms 2yrs	FAI, dysplasia	AP Pelvic, false profile and lateral axial radiographs; cross-sectional imaging (arthroscan or arthro-MRI) at investigator discretion	- Flexion-IR test
Sink et al., (2008)	35 participants, mean age 16years, 30 females, symptoms 3months to 3 years	Cam (6%) Pincer (43%) Combo (51%), ALT, cartilage involvement	MRI/MRA, AP Pelvic radiograph	- FADDIR

Tijssen et al, (2017)	77 active participants, (79 hips - 2 had bilateral arthroscopy), mean age 37 years (18-65), 35 females, mean duration of symptoms 3.2years	FAI plus ALT	Arthroscopy Radiographs ± MRI-A: α >50°, lateral CEA >39°, cross-over sign, protrusion acetabuli, joint space,	• FADIDR • FABER • Fitzgerald • Thomas test • Combined tests
Trindade et al., (2018)	603 participants symptomatic, unilateral FAI, mean age 36.4 ±12 years, 259 females	Cam-FAI	AP and cross-table radiographs: α >50°, pathological α ≤78°	• FABERs Distance Test
Troelsen et al., (2009)	18 participants, mean age 43 years (32-56), 16 females, with a history of periarticular osteotomies due to symptomatic, acetabular dysplasia	ALT, dysplasia	MRA Centre-edge angle 35° (29-40)	• FADDIR • FABER • Resisted SLR
Wang et al., (2011)	21 participants, mean age 31.7years (17-65), 12 females, 3-54months duration of symptoms	ALT, FAI	Cross table and frog leg radiographs: cam FAI = α > 50°; pincer + coxa profunda, cross-over sign or CEA >40°	• FADDIR

α alpha angle; ALT, acetabular-labral tear, AP, anterior posterior; CEA, centre-edge angle, FAI, femoroacetabular impingement; IAHP, intra-articular hip pathology; IR, internal rotation; IROP, internal rotation with over-pressure; NR, not reported; SLR, Straight leg Raise

Table 2-3: Summary of Articles

Test	Author		Participants (no. hips)	SN/SP (95% CI)	Likelihood ratio	PPV/NPV	Ref Standard
FADDIR	Casartelli et al. (2018)	Cam/pincer/ mixed	74	41 (18-67) / 47(34-61)	0.78(0.41-1.45) / 1.24(0.77-2.01)	19(8-35)/ 73(56-86)	MRI
		Cam or mixed		60 (26-88) /52(39-64)	1.24(0.7-2.18) /0.78(0.35-1.72)	16(10-25)/ 89(79-95)	MRI
	Hananouchi et al., (2012)	FAI only	69 (107)	56 (37-73)/83(31-98)*	3.3/0.53*	100/15.4	MRI
	Kapron et al., (2012)	Cam	65				Radiographs
	Laborie et al., (2013)	FAI	1170				Radiographs
	Martin et al., (2008)	FAI/ALT	105	78 (59-89) / 10(3-29)	0.86/2.3	*53(38-67)/25(7-59)	Intra-articular injection

	Sink et al., (2008)*	FAI	35	99(87-100) /17(2-69)	1.2/0.09	57(39-73) /50(5-95)	Radiographs
		Labral		97(77-100)/ 4(0-28)	1/0.76		MRI
	Troelsen et al., (2009)	ALT	18	59/ 100	2.3/0,56*	100 /13	MRA
	Wang et al., (2011)*	ALT	21	96(73-99) / 6(1-37)	1/0.7	61(41-79) / 50(5-95)	Radiographs
FABER	Kapron et al., (2012)	Cam	65				Radiographs
	Maslowski et al. (2010)	FAI/ALT	50	82(57-96)/25(9-48)		46(28-65)/ 64(27-91)	Intra-articular injection
	Martin et al., (2008)	Various IAHP	105	60(41-77)/ 18(7-39)	0.73/2.2	45.5 (29.8, 62)/ 28.6 (11.7,54.6)*	Intra-articular injection
	Tijssen et al., (2017)	FAIS plus ALT	77(79)	81(70-88) / 0(0-95)	0.81(0.72-0.9)		Arthroscopy
	Troelsen et al., (2009)	ALT	18	41 / 100		100 / 9	MRA

FDT	Trindade et al. (2018)	Cam	603	85(79-89)/38(35-39)		35(33-37)/86(81-90)	AP Radiograph
IR at 90° Flex	Mayes et al., (2016)	ALT	98	50(26-74) /96(77-99.8)			MRI
	Maslowski et al., (2010)	Various IAHP	50	91(68-99) /18(5-40)		47(29-64) / 71(25-98)	Intra-articular injection
	Nogier et al., (2010)	FAI, dysplasia	241	70/44	1.3/0.69*	63/53	Radiographs
	Sink et al., (2008)*	Cam	35	97(77-100) / 4(0-28)	1/0.76		Radiographs
Flex IR plus Compression	Narvani et al., (2003)	ALT	18	75(19.4-99.4) / 43(17.7-71.7)	1.3/0.58*	27.3(9.7, 56.6)/85.7(48.7,97.4)*	MRA
THIRD	Myrick & Nissen (2013)	ALT	100	98(93-100) / 75(19-99)		99(94-100) / 60(15-95)	Arthroscopy
Squat	Ayeni et al., (2014)	Cam	76	75/41	1.3/0.61	47.1(34.1,60.5)/ 70.4(51.5.84.1)*	MRI/MRA

	Murphy et al., (2017)	Cam	21				Radiographs
Resisted SLR	Troelsen et al., (2009)	ALT	18	6/100		100/6	MRA
	Maslowski et al., (2010)	Various IAHP	50	59(34-82) / 32(14-55)		41(22-62) / 50(23-77)	Intra-articular injection
	Tijssen et al., (2017)	FAIS plus ALT	77(79)	21(12-32) / 0(0-95)	0.21(0.14-0.33)		Arthroscopy
Scour	Maslowski et al., (2010)	Various IAHP	50	50(26-74) /29(12-51)		36(17-57) / 42(18-69)	Intra-articular injection
	Tijssen et al, (2017)	FAIS plus ALT	77(79)	50(35-65)			Arthroscopy
Thomas	Narvani et al., (2003)	ALT	18	25/ -			MRA
	Tijssen et al., (2017)	FAIS plus ALT	77(79)	11(5-20) /67(13-98)	0.33(0.06-1.8)/1.34(0.89-2.01)		Arthroscopy
Fitzgerald	Tijssen et al., (2017)	FAIS plus ALT	77(79)	72(61-82) / 33(2-87)	1.08(0.48-2.45)/ 0.83(0.16-4.41)		Arthroscopy

*SN, sensitivity; SP, specificity; PPV, positive predictive value; NPV, negative predictive value. *data reproduced from Reiman et al., (2015)*

2.2.2 Results

Initial searches retrieved 1,850 titles. After screening titles, abstracts and removing duplicates, this reduced the number to 53 articles. Following the application of inclusion/exclusion criteria, 17 papers met the criteria for review, with a total of 2892 participants and 11 diagnostic tests being found in the papers.

Eight studies examined the flexion-adduction-internal rotation (FADDIR) impingement test. Six studies investigated the flexion-abduction-external rotation (FABER) test, six investigated internal rotation (IR) at 90° flexion, three investigated the resisted SLR test, two the scour test, Thomas test and squat, and one paper each for FABERs Distance Test (FDT), flexion IR plus compression (IROP), the THIRD test, Fitzgerald test and range of movement. Additional data was also considered which was published by Reiman et al., (2015) who performed statistical analysis on studies where this information had not been previously calculated. Due to study heterogeneity, a meta-analysis and formal systematic review was not conducted. Table 2-2 presents the demographics and the characteristics of the included studies. Table 2-3 presents the diagnostic tests investigated along with their diagnostic accuracy.

2.2.2.1 *FADDIR*

Eight studies, with 1634 participants included diagnostic information on the FADDIR anterior impingement test. The majority of studies found a high level of sensitivity (SN) but a poor level of specificity (SP) (see Table 3) in the diagnosis of FAIS and/or ALT. Two studies, despite not reporting favourable SN data, advocated the use of FADDIR impingement test based on high SP (Hananouchi et al., 2012) and high positive predictive values (PPV) (Troelsen et al., 2009; Hananouchi et al., 2012). This was not supported in the remaining studies. Casartelli et al., (2018) was the only paper to report low SN values (41%) for the FADDIR test but these levels increased once isolated pincer morphology was excluded (60%).

2.2.2.2 *FABERs*

Seven studies, with a total of 919 participants, reported on the diagnostic accuracy of FABERs test: 5 in those with FAI and/or ALT, and one in patients with intra-articular hip pathology (IAHP). In four studies (Martin et al., 2008; Troelsen et al., 2009; Maslowski et al., 2010; Wang et al., 2011), a positive test was recorded as one which provoked pain or symptoms. Kapron et al., (2012) and Tijssen et al., (2017) deemed pain and/or restriction in range as a positive test. Of these 6 studies, only 4 reported data on diagnostic accuracy (see Table 3). The one remaining FABERs study (Trindade et al., 2018) looked purely at the 'FABERS distance test' (FDT). This study demonstrated that the FDT is correlated with the alpha angle and is a good diagnostic examination for pathological cam-type FAI as defined by alpha angle equal to or greater than 78° (SN 85%, 95%CI 79-89; SP 38%, 35-39%). This review showed that in the diagnosis or FAIS and/or ALT, FABERs test has moderate to high SN and low SP.

2.2.2.3 *Internal Rotation*

Six studies, with 614 participants, examined variations of internal rotation at 90° hip flexion with moderate-high SN (50-98%) and conflicting findings for SP (4-96%). One paper examined IR with over-pressure (Maslowski et al., 2010) with good SN but poor SP (SN 91% 95% CI 68-99%; SP 18% 95%CI 5-40%; PPV 0.47(0.29-0.64) NPV 0.71(0.25-0.98)), and another examined Flexion-IR plus compression and showed less SN and low-moderate SP (75% and 43% respectively) (Narvani et al., 2003). One further study reported on the Hip IR with Distraction (THIRD) test in the diagnosis of ALT (Myrick and Nissen, 2013), this was however a low-quality study based on its high risk of bias and applicability.

2.2.2.4 *Other assessments*

Three papers (Troelsen et al., 2009; Maslowski et al., 2010; Tijssen et al., 2017) reported on the Resisted Straight Leg Raise (SLR) test, also known as the Stinchfield manoeuvre, with conflicting statistical findings (see Table 2-3). The Scour test, also known as the hip quadrant test, was reported into two studies although there was a disparity in the cohorts used and in the testing procedure, with Maslowski et al (2010) advocating the inclusion of a compression force whereas Tijssen et al., (2017) did not. The test was reported to be only 50-62% SN and 29-38% SP in the diagnosis of a variety of IAHPs. Two studies (Narvani et al., 2003; Tijssen et al., 2017) considered the Thomas test for the diagnosis of ALT, whereby the hip is extended from a flexed position and is deemed positive in the presence of a pain or a click (Tijssen et al., 2017). Neither study found the test to be sensitive or specific. Tijssen et al., (2017) also considered another ALT provocation test, the Fitzgerald test. Although in isolation this test was shown to have good SN (72%; 95% CI 61-82%) it has poor SP (33%) and likelihood ratios (positive 1.08, negative 0.83).

Two studies examined the diagnostic utility of squatting in the diagnosis of cam-type FAI. Ayeni et al., (2014) found that pain provocation during maximal squat depth had moderate SN (75%; 95% CI 56.6-88.5%) and low SP with modest positive and negative likelihood ratios (1.3, 0.6). Murphy et al., (2017) did not report pain provocation on squatting and found no statistically significant correlation between squat depth and cam-deformity.

2.2.3 Discussion

Diagnosis of FAIS is dependent upon the presence of clinical signs in combination with radiology and symptoms (Griffin et al., 2016). The aim therefore of this literature review was to identify and understand the accuracy of the clinical tests used in the assessment and differential diagnosis of individuals with FAIS. The low number of high-quality studies coupled with the lack of homogeneity between study participants, methodology and reference standards, meant that it was not possible to use meta-analysis.

2.2.3.1 *FADDIR*

When considering the FADDIR test, sometimes documented as the anterior impingement test, most studies found a high level of SN but a poor level of SP. This reinforces the findings reported in the meta-analysis by Reiman et al., (2015) who published a pooled SN of 94% and SP of 9%.

Casartelli et al., (2018) was the only paper to report low to moderate SN values in the assessment of ice-hockey players with FAI-morphology, however in this study, an alpha angle of >60° was used to identify cam-morphology. This was higher than any of the other studies considering the FADDIR test. This may explain the lower SN values reported here and potentially lead to inaccurate interpretation of the test in other studies.

2.2.3.2 *FABERs*

The FABERs test for pain provocation, which looks at the combined motion of flexion-abduction-external-rotation, similarly demonstrated moderate to high SN and low SP. This infers that the test may help identify those with IAHP, but it is not precise enough to identify the structure at fault. Clinicians must proceed with caution during this test as it was originally described as a diagnostic for sacro-iliac pain (Byrd, 2007) and hence location of pain provocation will be key.

The FABERs distance test, which has been shown as a reliable hip ROM test (Bagwell, Bauer, et al., 2016), showed a positive correlation with presence and size of cam deformity (Trindade et al., 2018). A positive test was deemed as a limb-to-limb difference of ≥4cm.

2.2.3.3 *Internal Rotation*

Studies looking at the Flexion-IR assessment, demonstrated high levels of SN and but conflicting reports on test SP. This is not dissimilar to the pooled findings reported by Reiman et al., (2015) on the use of the Flexion-IR test for diagnosis of impingement and/or ALT (SN 96%, SP 25%). It is, however, difficult to draw conclusions from these findings due to disparity in how the test was carried out alongside the homogeneity of study participants. One study each included: over-pressure (Maslowski et al., 2010), compression (Narvani et al., 2003) and distraction (Myrick and Nissen, 2013) and two of the studies included patients with a variety of IAHP (Maslowski et al., 2010; Narvani et al., 2003).

Another study showed that hip IR range significantly correlated with alpha angle, regardless of whether the measure was taken in supine, sitting or prone. They reported high SN values and moderate SP (Kapron et al., 2012) which echoes the previous findings of Wyss et al., (2007). Murphy et al., (2017) did not concur with these findings reporting no correlation between cam-morphology and range of motion reported on a flexion-IR test. However, their sample size was low and there was a reduction, albeit non-significant, in range reported on the symptomatic side compared with the asymptomatic limb. A limitation in the studies by Kapron et al., (2012) and Murphy et al., (2017) was the sole use of radiographs as reference test, meaning it is unclear whether presence of cam represented morphology or pathology.

Other studies (King et al., 2018; Tak et al., 2016) have reported similar restrictions in hip rotation in hip-groin pain patients irrespective of cam-morphology. While Chadayammuri et al., (2016) found a correlation between passive IR, femoral torsion, and acetabular version. This all raises further questions as to whether hip range of motion provides diagnostic value in both the identification of both morphology and/or pathology. Further research is warranted to better understand this area.

Kapron et al., (2012) found that in 65, predominantly symptom free, college footballers, 95% of all hips showed at least 1 radiographic finding of FAI morphology. Yet, only 11 were painful on testing FADDIR and 3 hips were painful on testing FABERs distance test. Conversely, Laborie et al. (2013) found that radiographic cam-type findings were associated with a positive impingement test in males for a composite score value of one or two radiographic findings (p = 0.043, 0.05). They did not find the same correlation for more than 2 radiographic features or find a correlation in female participants. It may be that impingement testing does not identify the presence of morphology but may only identify those with secondary pathology such as ALT or chondral lesions. As neither study included 3-dimensional imaging, this assumption cannot be validated.

2.2.3.4 *Clustering Assessments*

Tijssen et al., (2017) postulated that pooling physical tests alongside patient history would lead to greater diagnostic accuracy for FAIS/ALT. In isolation, they found 2 clinical tests with SN greater than 80% (FADDIR 91%; FABER 81%) but found that in combination or when FABER was combined with a subjective report of '*groin as main location of pain*', SN increased to 97%. All combinations however showed poor SP, and only the Thomas test in isolation showed moderate SP. This may reflect the target population as all participants underwent arthroscopic surgery. Maslowski et al., (2010) also analysed clusters of physical tests and found improved SN with combinations of 2, 3 and 4 tests but this was accompanied by a decline in already low SP levels. The effect of cluster testing warrants further investigation with more robust methodology, as this reflects the reality of diagnosis in clinical practice but also strengthens the concept that FAIS is a '*triad of symptoms, clinical signs, and imaging findings'* (Griffin et al., 2016) which does not view any one component in isolation.

2.2.3.5 *Squat*

Squatting was the only functional diagnostic test identified in this review although it is not possible to compare findings due to the differing protocols used. Although Murphy et al., (2017) found no correlation between squat depth and cam deformity, the differences in squat depth reported may be clinically relevant in the sporting population with several other studies supporting the finding that squat depth is diminished in FAIS subjects (Diamond et al., 2017; Lamontagne et al., 2009; Ng et al., 2015; Ng et al., 2016). Reiman et al., (2015) also reported the bilateral squat to maximum depth as published by Ayeni et al., (2014) had the greatest shift in pre- to post-test probability (6.1%), therefore, squat depth, with and without symptom provocation can be considered potentially useful as a screening tool. The weakness of the Murphy et al. (2017) study was small sample of participants with cam-morphology.

2.2.3.6 *Limitations*

A significant methodological limitation of this review is the inconsistency of the reference standards used in which to confirm presence of pathology. To ascertain the diagnostic utility of a clinical assessment, the appropriate reference standard must be utilised to ensure accurate analysis. A large portion of the diagnostic studies had been conducted on surgical candidates, and, in one case (Troelsen et al., 2009), all candidates had undergone periarticular osteotomies. Although surgery for FAIS has increased significantly over the past decade (Reiman & Thorborg, 2014), FAIS would appear to sit on a spectrum of asymptomatic morphology to varying degrees of pathology, not all of whom may require surgical intervention. Although arthroscopy is seen as the most accurate method of assessing IAHP

(Alradwan et al., 2015), it is not ethically appropriate, clinically justified or financially viable to use this diagnostically in all cases of hip and groin pain. Two studies used arthroscopic hip surgery as reference standard (Myrick & Nissen, 2013; Tijssen et al., 2017), and several others used pre-surgical candidates, therefore a high prevalence of more disabling cases of FAIS can be expected in these cohorts. Surgical candidates would appear to be a specific sub-group within this syndrome presenting with the more severe stage of disease progression. This makes interpretation and generalisability of results in these publications more challenging.

Eight studies employed plain radiographs for the identification of FAI-morphology: pure cam (Kapron et al., 2012; Murphy et al., 2017; Trindade et al., 2018), or combined/mixed morphology (Sink et al., 2008; Nogier et al., 2010; Wang et al., 2011; Laborie et al., 2013; Tijssen et al., 2017). All bar one study, (Murphy et al., 2017) performed an anterior-posterior (AP) radiograph plus an orthogonal view: either a cross table, Dunn, frog-leg lateral, Lequense false or a Ducroquet. It is recommended that both views should always be done together (Johnston et al., 2008) as the AP allows visualisation of the acetabulum (Tannast et al., 2007) while oblique views are necessary to visualise the proximal femur (Griffin et al., 2016). Murphy et al., (2017) only utilised a 90-degree Dunn view as their reference test which may underestimate the degree and prevalence of FAI in their cohort (Rakhra et al., 2009).

Although plain radiographs are important in the initial diagnosis of FAIS due to their ability to exclude other conditions such as fracture, dysplasia, and osteoarthritis (Tannast et al., 2007; Griffin et al., 2016), it is also recommended that three-dimensional (3D) imaging is used to allow for a more detailed assessment (Griffin et al, 2016). Only two studies (Sink et al., 2008; Wang et al., 2011) which employed plain radiographs went on to include 3D assessment in all participants. 3D imaging has the additional benefit of identifying intra-articular pathology of the acetabular labrum, chondral abnormalities, (Tannast et a., 2007; Barton et al., 2011; Griffin et al., 2016) and soft tissues lesions (Griffin et al., 2016), which may develop because of FAI. Without this level of information, it becomes unclear whether the study participants have pathological FAIS or merely bony morphology which limits the interpretation of test accuracy.

Seven studies (Narvani et al., 2003; Sink et al., 2008; Troelsen et al., 2009; Hananouchi et al., 2012; Ayeni et al., 2014; Mayes et al., 2016; Casartelli et al., 2018) utilised either magnetic resonance imaging (MRI) or magnetic resonance arthrography (MRA) as reference standard. Only 2 studies used 3-Teslar MRI (Hananouchi et al., 2012; Mayes et al., 2016) which is known to be highly accurate for evaluating the labrum and acetabular cartilage in patients with clinically suspected FAI (Dorota et al., 2017). The remaining studies that employed MRI, used either 1.0 or 1.5-Teslar which is known to only have modest SP for labral pathology, high SP for chondral damage but poor SN (Byrd & Jones, 2004; Smith et al., 2013). Four studies used MRA which improves the SN of detecting labral tears relative to MRI, but it has also shown to over report labral pathology (Byrd & Jones, 2004). It should be considered that imaging may have identified asymptomatic labral tears which are known to be common in asymptomatic individuals (Frank et al., 2015; Heerey et al., 2018).

The reference standards used in these studies have no ability to detect the true pain-provoking structure, yet as most clinical diagnostic tests under investigation, by definition, are deemed positive by pain or symptom provocation, correlation between the two can be somewhat difficult. The inclusion of intra-articular hip injection (IAHI) as was the case in two studies (Martin et al., 2008; Maslowski et al., 2010), may aid in the ability to distinguish between intra and extra-articular source of pain and have been shown to be diagnostically reliable in 90% of cases (Byrd and Jones, 2004). Martin et al., (2008) found that despite ALT on MRA, 43% of individuals did not respond positively to IAHI, reinforcing that in those cases, the labrum may not have been the source of pain. This may explain why in this study the FADDIR impingement test was shown to be moderately SN but not SP.

Another limitation of the studies reviewed is the lack of standardisation in the criteria used to define morphology. The alpha angle, originally described by Nötzli et al., (2002), quantifies cam morphology by measuring the extent to which the femoral head deviates from spherical (Agricola et al., 2014). Agricola at al. (2014) proposed a 60° threshold distinguinshing between normal hips and those with cam-morphology, and a 78° alpha angle for the identification of a pathological cam, indicating an increased risk of developing OA. Of the 12 papers identified for this review which included participants with cam-type FAI, only 3 papers (Murphy et al., 2017; Casartelli et al., 2018; Trindade et al., 2018) utilised alpha angles ≥60°. The remaining studies did not specify the angle used, or used angles <60°. It has already been reported that alpha angles <60° do not distinguish between symtomatic and asymptomatic-cam (Sutter et al., 2012) therefore studies which employed these angles have limited diagnostic accuracy in understanding the assessment of FAIS.

One study (Laborie et al., 2013) employed different alpha angle thresholds for males and females (≥83° and ≥57° respectively) based on a proposal by Gosvig et al., (2007). However, it has since been proposed that a non-sex specific threshold should be used as the lower prevalence of cam-deformity in females distorts the mean-group angles, but not the threshold at which pathology ensues (Agricola et al., 2014). For the presence of pincer-morphology, most studies in this review used the cross-over sign and/or centre edge angle as diagnostic criteria for the identification of focal or global acetabular over-coverage (van Klij et al., 2018) There is a lack of high quality evidence available to support the best radiographic criteria for diagnosis of pincer-FAI (Rhee et al., 2017), which is potentially reflective of the lower prevalence of pincer morphology relative to cam (van Klij et al., 2018).

2.2.4 Conclusion

FADDIR impingement test, IR at 90° flexion, and FABERs test showed moderate to high levels of sensitivity but poor levels of specificity, inferring that clinical diagnostic tests can identify IAHP, but they are unable to detect which structure is responsible. The findings, therefore, did not significantly enhance the work previously published by Reiman et al., (2015) who reported that few clinical tests make a significant change in post-test probability for the likelihood of FAI/ALT existing.

More recent literature identified that clustering of clinical tests may improve diagnostic accuracy but to date this still lacks specificity. The FDT also appears to be a potentially useful screening tool in the detection of larger cam morphology in a symptomatic cohort. Ultimately, two sets of diagnostic clinical tests may be required: one to identify morphology and one to identify pathology, but more high-quality homogenous trials with vigorous methodology are required to achieve this. To continue to try and understand and identify which individuals will progress from asymptomatic morphology to the development of FAIS, more work is required to establish robust, clinical tools which help to distinguish between these two states.

2.3 A narrative review of the physical and functional impairments associated with the presentation of FAIS

Injuries are both complex and multifactorial. The high prevalence of cam-type FAI morphology in the athletic population (Frank et al., 2015), compared to the relatively lower prevalence of FAIS, is reinforcement that bony morphology in isolation is not responsible for the aetiology of pathology and symptoms (Bagwell et al., 2016b).

It is recognised that appropriately developed physical qualities are associated with a reduction in injury risk (Gabbett, 2016), however in the case of FAIS, the cause-effect relationship between biomechanics, physical qualities and morphology is unclear. The aim of this narrative review is therefore to synthesise what is currently known regarding the functional biomechanical variables and physical qualities associated with the presentation of FAIS, across both athletic and non-athletic cohorts in attempt to deepen understanding of the topic. Identifying all potential contributing factors in this manner is an important component in the understanding of injury causation.

The findings from this review will be used to identify potential risk factors that will be taken into the experimental chapters of the thesis.

2.3.1 Methods

A comprehensive literature search was conducted using the electronic databases, MEDLINE, EMBASE and CINHAL. Further articles were retrieved by screening reference lists and citation searches of identified literature (Greenhalgh & Peacock, 2005) and through following relevant researchers and journals on social media. This was conducted by the lead author (E.J.A).

The search conducted from January 2000 to submission as per 2.2.1.1. The electronic searches were conducted by combining the following terms: *IAHP, hip pain, hip impingement, femoroacetabular impingement, FAI, FAIS, Cam, Cam morphology, pincer, pincer morphology, pelvis, strength, muscle strength, motor control, neuromuscular, range of motion, range of movement, range, movement, impairment, balance, proprioception, function, kinetics, kinematics, biomechanics, gait, squat.*

A narrative review was chosen due to the broad nature of this topic area. After screening titles and abstracts from the preliminary search, all articles written in English which provided insight into the functional and/or physical presentation of patients with FAIS were accessed. Findings were grouped by theme, synthesised, and presented in the following sections.

2.3.2 Hip joint range of motion

FAIS is associated with restricted range of movement (ROM), typically demonstrating a loss of internal rotation (IR) in flexion (Griffin et al., 2016) which has been shown to correlate with bony anatomy of the hip (Wyss et al., 2007; Kapron et al., 2012; Mosler et al., 2018) but not to correlate with ALT (Mayes et al., 2016). Audenaert et al., (2012) found a significant reduction in passive flexion and IR in those with symptomatic cam morphology ± mix presentation FAIS when compared with a cohort of asymptomatic FAI and a control group. No significant difference was found when comparing range of movement between asymptomatic individuals and controls. There was however a 5° discrepancy in hip flexion range between asymptomatic and controls which may be clinically relevant in the sporting population. The same group (E. A. Audenaert et al., 2012) reported a similar pattern of movement when looking at 3-dimensional reconstructions of CT scans however in this instance there was a significant difference in IR in all 3 sub-groups (12.3° FAIS, 21.1° asymptomatic FAI, 27.9° control). These studies both recruited pre-arthroscopy patients, whereas Brunner et al., (2016) found no difference in passive hip ROM in any direction in national level ice hockey players when comparing symptomatic and asymptomatic FAI verses healthy control while Sink et al., (2008) report a significant loss of IR in adolescents when comparing the symptomatic with the asymptomatic limb. Other studies recruiting pre-operative patients have reported

ROM between the symptomatic limb and the asymptomatic limbs in those with FAIS. The findings have been conflicting with some reporting no differences (Chloisy et al., 2009) while others reporting significant reductions in flexion (Nepple et al., 2015), abduction (Philippon et al., 2009; Nepple et al., 2015), adduction, IR, and external rotation (ER) (Philippon et al., 2009).

Wyles et al., (2017) completed a 5-year prospective study in adolescent athletes and found that limited hip flexion and IR on initial assessment, alongside a positive impingement sign and presence of cam morphology, were associated with increased degenerative changes on MRI and radiographs. The majority of these cases however, remained asymptomatic despite reporting lower functional scores. Of the 26 hips with limited ROM, six demonstrated progression towards mild-osteoarthritis as categorised by the Tönnis radiological classification system (Grade 1 Tönnis) whereas all hips in the control group remained Tönnis grade 0. Previous work in middle-aged adults has identified those with significant cam deformity and loss of internal rotation are at risk of fast progression to end-stage hip OA (Rintje Agricola et al., 2013; Nicholls et al., 2011). The average age of participants in the Wyles et al (2017) study was 21.3 years; long term follow-up of this cohort may therefore add further knowledge to the role of restricted range of movement in the accelerated development of FAIS and osteoarthritis.

Many studies utilised a goniometer in the measurement of ROM (Philippon et al., 2009; Chloisy et al., 2009; Brunner et al., 2016; Tak et al., 2016; Wyles et al., 2017). When compared with an electromagnetic tracking system, goniometry is shown to have similar intra-class coefficients, coefficient of variation, standard error of measurement and random errors, however, it is also known to over report hip ROM in those with FAIS (Nussbaumer et al., 2010). This makes comparison of raw data between studies difficult. Brunner et al., (2016) attempted to limit error by using a validated clinical examination chair which has been shown to be more reliable in the reporting of hip IR (Reichenbach et al., 2010). Two other studies employed three-dimensional (3D) computed tomography (CT) and found a significant reduction in hip flexion, IR in 90° flexion and abduction in individuals with FAIS compared with controls (Kubiak-Langer et al., 2007). Although this software has been shown to be an accurate assessment of FAI-morphology, with moderate reliability (Beaulé et al., 2005), it does not take into account soft tissue or cartilaginous structures which may contribute to restrictions in ROM. Consequently, the ranges may be over-estimated and therefore cannot be transferred to the clinical setting.

Only one study reported dynamic ROM of the hip (Kennedy et al., 2009) reporting significantly less IR, ER and abduction in those with cam FAIS compared with an asymptomatic control group. There was a meaningful difference in those figures reported for dynamic flexion and IR by Kennedy et al., (2009) compared with the passive figures reported by Audenaert et al., (2012) in both the symptomatic and control groups which highlights the role the soft tissue structures play in limiting and controlling ROM.

Tak et al., (2016) screened 60 professional football players and found a significant reduction in IR and total rotation (TR) in those players with a history of hip and groin symptoms (HGS) which resulted in time lost from training compared to those with no time loss, independent of the presence of cam morphology. A similar reduction of IR, independent of cam-morphology, has also been reported in Australian Football players (Murphy et al., 2017). Tak et al., (2016) also found that those players most affected by HGS as measured by the Copenhagen Hip and Groin Outcome Scores (HAGOS), had a significant reduction in IR and TR regardless of the presence of cam morphology. Those individuals with cam morphology presented with reduced hip IR and TR and increased ‘bent-knee fall-out’ (BKFO), however, these differences were shown to be not statistically significant. King et al., (2018) also found a reduction in ER in the symptomatic limb of 15 sub-elite footballers when compared with the asymptomatic limb despite the fact there was no difference between symptomatic and asymptomatic limb for the presence of bony morphology. Mosler et al., (2018), in a large cohort of asymptomatic football players, found an association between cam morphology and a reduction in IR and BKFO, as well as pincer morphology and lower abduction ROM, although they report these associations to be weak. The findings from each of these studies (Tak et al., 2016; King et al., 2018; Mosler et al., 2018) may support the theory that bony morphology in isolation does not lead the development of the symptomatic state that is FAIS.

Although FAIS would appear to be accompanied by a reduction in hip joint ROM, these studies do not provide clarity on whether a reduction in hip joint range of motion contributes to, or is a consequence of, FAIS.

2.3.3 Pelvic tilt

Pelvic tilt changes the orientation of the acetabulum; therefore, it has the potential to either contribute to, or protect from, FAI pathomechanics. Changes in pelvic tilt may be dynamic or morphological, the latter is known as pelvic incidence (Pierannunzii, 2017). A recent systematic review identified that FAI pelves have a lower pelvic incidence than in controls. This is expected to reduce the posterior pelvic tilt available thus increasing the risk for impingement (Pierannunzii, 2017).

3-dimensional modelling of computerised tomography (CT) scans has shown that a 10° increase in anterior pelvic tilt from an individuals' native resting position in supine, resulted in a significant decrease in total hip IR in flexion by 5-9° (p <0.001) with an anterior shift in femoral and acetabular location positions. Conversely, a 10° increase in posterior tilt resulted in a 5.1° increase in IR, a superior lateral shift in femoral impingement and a superior-lateral shift in acetabular impingement location (Ross et al., 2014). This is because anterior tilt decreases acetabular version and increases femoral head coverage (Dandachli et al., 2013). This relationship between the pelvis and hip rotation is further supported by the work of Bagwell et al., (2016) who have shown that for every 5° of anterior pelvic tilt, there is 1.2-1.68° reduction of hip IR and the reverse is seen for posterior tilt and ER. In the presence of morphology, the pelvic orientation can clearly be seen to influence the point at which bony abutment between the femoral neck and the acetabulum occurs. This has been further compounded by Ng et al., (2015) who found that in the presence of cam deformity, decreased femoral neck-shaft angle in conjunction with a reduction in pelvic range of motion can distinguish between those with FAIS from those with asymptomatic morphology and healthy controls.

Van Houcke et al., (2014) demonstrated that posterior pelvic tilt during active hip flexion is increased in individuals with FAIS, but not when the task is performed passively. An additional

10° posterior tilt is shown to enable an increase in 10° hip flexion, the reverse is seen with anterior tilt (Ross et al., 2014). It is likely that the increase in posterior tilt reported by Van Houcke et al., (2014) is an active attempt to avoid impinging while compensating for a loss of isolated hip flexion ROM which was demonstrated in both the active and passive groups. The findings of Azevedo et al., (2016) conflicted with those of Van Houcke et al., (2014) reporting that FAIS patients demonstrate less posterior pelvic rotation during active hip flexion to 45° and 90° when compared to controls and those with other symptomatic hip conditions. The key difference between these two findings is that Van Houcke (2014) performed the task in supine whereas Azevedo et al., (2016) performed the movement in standing. This would change the relative contribution required from the neuromuscular system.

An increase in anterior tilt, be it bony or dynamic, is predicted to result in the earlier occurrence of impingement (Ross et al., 2014) which may contribute to the onset of FAIS. Pelvic morphology and kinematics should therefore be taken into consideration when screening and planning appropriate interventions for those with FAI.

2.3.4 Hip strength

The findings of literature relating to hip muscle strength in pre-surgical FAIS candidates are variable. When considering isometric maximal voluntary contraction (MVC), Casartelli et al., (2011) reported a significant reduction in hip adduction (28%, $p = 0.003$), flexion (26%, $p = 0.004$), external rotation (18%, $p = 0.04$) and abduction (11%, $p = 0.03$), but no difference in hip internal rotation or extension when compared with controls. Diamond et al., (2016) also reported a reduction in hip abduction strength, albeit much larger than Casartelli et al., (2012) (20%, $p = 0.04$) but they found no significant reduction in isolated force production in any of the other muscle groups. One explanation for this difference in findings between these two studies may be the exclusion of isolated pincer-type FAIS in the latter study whereas Casartelli et al., (2011) included all sub-types of morphology. The final study only declared participants to be surgical candidates for undefined intra-articular pathology. Freke et al., (2018) also reported significant deficits in hip muscle strength compared with all controls. In this study deficits were seen in all directions (22-35%, *p* <0.05) but only in hip abduction and extension when compared with the non-surgical limb (11%).

Although Diamond et al., (2016) did not find a difference in strength of the hip rotators, the ratio of isometric ER/IR strength was shown to be significantly higher in the symptomatic cohort (*p* = 0.01). There were no differences found in ratios for any of the other muscle groups. This warrants further investigation as the local muscles of the hip, including the deep internal and external rotators, are believed to reduce hip joint forces by providing dynamic stabilisation (Retchford et al., 2013) therefore any weakness, inhibition, or change in synergistic relationships may lead to poor control of the joint or undesirable movement patterns. Assessment of MVC in isolation will only partially explore this premise, especially as this process will not identify individual muscle contribution. As we know, many individual muscles contribute to the 6 major movements that occur at the hip (Neumann, 2010).

Kierkegaard et al., (2017) examined both isometric and isokinetic MVC in cam, pincer, or combined type-FAIS. They found a 15-21% reduction in flexion strength, supporting the previous findings of Casartelli et al. (2011) and Nepple et al., (2015). However, Kierkegaard et al. (2017), also showed hip extension to be reduced by 10-25% in the symptomatic hip of those with FAIS which had not been previously reported. Subgroup analysis revealed that a higher-level of impairment was seen in female participants. As a reduction in force contribution from the gluteal muscles has been shown to increase the forces the hip joint is subjected to (Lewis et al., 2009), these findings may have significant implications in the development and management of FAIS. A limitation of the Kierkegaard et al., (2017) study was the omission of imaging for control participants. It is therefore unclear whether controls had any underlying morphology.

Kierkegaard et al., (2017) also reported a reduction in the rate of force development (RFD) of the hip extensors in both legs of FAIS patients, irrespective of unilateral or bilateral pathology. RFD, or the ability to rapidly produce force or torque, is known to have both neural and muscular determinants (Maffiuletti et al., 2016) and as most patients demonstrated significantly weaker, isometric and concentric, extensor strength in their symptomatic leg when compared with their contralateral leg (7-13%), supraspinal, protective mechanisms should be considered as an explanation for the symmetrical differences seen in RFD in those with FAIS. The work of Seijas et al., (2016) using tensiomyography, adds further insight, demonstrating that contraction time of gluteus maximus is impaired in the affected limb of those with FAIS (symptomatic limb 37±9.5ms, healthy limb 32.9±7.2ms; p =0.01) whereas maximal displacement is not. No differences in contraction time or displacement were found for Rectus Femoris or Adductor Magnus. Contraction times in excess of 30ms reflect a higher prevalence of type 1 muscle fibres (Macgregor et al., 2018; Rey et al., 2012), however, the asymmetry seen in this population may also signify a difference in ability to rapidly produce force (Rey et al., 2012). These findings may have significant implications for the athletic population when considering both health and performance.

Several studies have reported a reduction in hip flexor strength in FAIS (Casartelli et al., 2011; Casartelli et al., 2012), but Casartelli et al., (2012) found that although a hip flexor strength deficit was evident during isometric and isokinetic assessment, this was not accompanied by evidence of fatigue, and that rate of decline in isokinetic torque was comparable between the symptomatic and the control group (p >0.5). This may have implications for exercise prescription in those with symptomology however, as surface EMG was utilised in this study, data relating to iliopsoas and iliocapsularis was not available, and hence the full complement of hip flexors was not assessed. These two muscles are thought to be prime stabilisers of the femoral head (Lawrenson et al., 2017; Retchford et al., 2013) and key in attenuating force across the front of the joint (Lewis, et al., 2009) and hence their role in those with FAIS warrants further attention.

When comparing the symptomatic limb with the contralateral limb of patients with FAIS, Nepple et al., (2015) reported that only 46% and 42% of affected limbs showed a reduction in abduction (8.7%) and flexion (8%), and there was no reduction in isometric muscle strength in any of the other hip muscle groups. It has been shown that active individuals with chronic hip joint pain (CHJP) also demonstrate weakness in the contralateral, uninvolved limb (Harris-Hayes et al., 2014) which may explain the findings in this study. Magnitude of hip flexion strength deficit in this cohort was however associated with hip flexion range of motion and size of ALT. Both flexion and ER strength correlated with function, as assessed by a modified

Harris Hip Score (Nepple et al., 2015). Kierkegaard et al., (2017) also found a similar positive relationship between patient reported outcome measures and flexion and extension strength. Interestingly, the asymptomatic limb of 5 participants in the Nepple et al., (2015) study had an alpha angle >55° but a negative impingement sign reinforcing the known prevalence of cam and pincer morphology in the asymptomatic population (Ng et al., 2015; Reichenbach et al., 2010). There was however no reported sub-analysis of hip strength in this group which may have provided further insight into the role of disease progression in those with underlying morphology.

Two studies reported on isometric hip strength in patients with ALT in which neither study reported underlying bony morphology. Mendis et al., (2014), found a significant reduction in hip flexor muscle strength compared with controls (p <0.01) and Tsai et al., (2004) found a significant reduction in hip adduction strength but no difference in abduction strength in 22 athletes pre-operatively when comparing the involved limb with the uninvolved side (p = 0.032). In the latter study, the difference was not seen in patients' post-arthroscopic repair. The acetabular labrum is believed to contribute to stability of the hip joint through increased joint congruency, control of femoral head translation and joint proprioception (Retchford et al., 2013), therefore repair of this structure, alongside convalescence and rehabilitation, may explain the improvement in strength seen in this cohort. The reduction in hip flexion strength reported by Mendis et al., (2014) was not accompanied by a reduction in hip flexor muscle size (p >0.17) or recruitment pattern (p >0.53). Muscle atrophy has not been widely reported in patients with FAIS, but it has been shown to be present in some, but not all muscle groups of individuals with advanced OA, although not in those with mild pathology (Grimaldi et al., 2009). The only hip flexor considered in the Grimaldi et al., (2009) study was Tensor Fascia Latae (TFL), which showed no sign of muscle atrophy regardless of disease progression. This may explain the lack of hip flexor atrophy reported by Mendis et al., (2014).

The majority of findings relating to hip strength relating to FAIS has been in those individuals listed for surgical intervention inferring an advanced stage of the syndrome. To further understand the progression of FAIS and the role of the musculature on this, the younger, athletic population and those with less advanced pathology must be considered. King et al.,

(2018) found no difference in hip strength scores in sub-elite footballers with HRP and a positive impingement test when comparing with the contralateral limb. Elite soccer players have been shown to be stronger in their dominant limb adductors (3%) and abductors (4%) compared with their non-dominant side (Thorborg et al., 2011). As 87% of the subjects in the King et al., (2018) study were right-foot dominant and 73% were symptomatic on the right side, this may explain the lack of difference seen in the hip strength scores of these players. Both Thorborg et al., (2011) and Kemp et al., (2013) advocate the use of the unaffected limb as a comparator for assessment, however, the findings of Harris Hayes et al., (2014) plus the limited data available on those in high performance sport, make it difficult to transfer these findings to the elite athletic population.

Harris-Hayes et al., (2014) assessed the hip strength of young adults with CHJP who were not considered surgical candidates. Each participant had a positive FADDIR impingement test but only 10 of 35 demonstrated FAI morphology on MRI. The study group displayed a significant reduction in hip rotation and abduction strength (16-18%) compared with asymptomatic controls. Further analysis found no difference in hip strength profiles of those with FAI morphology and those without, although as with many of these studies, it is difficult to draw firm conclusions due to the small sample size.

Deficits in strength may not purely result from muscle weakness but may signal alterations in neuromotor control, pain inhibition or fear avoidance (Mendis et al., 2014). Casartelli et al., (2011) found an impaired ability to activate TFL, but not Rectus Femoris, during an active hip flexion task in those with FAIS, while Diamond et al., (2017) reported an alteration in the co-ordination of the deep hip muscles during gait when compared with asymptomatic controls without morphology. Lawrenson et al., (2020) also reported differences in muscle activation between football players (soccer and Australian rules) with FAIS verses controls. In this study, those with FAIS showed similar activity in the iliocapsularis muscle between active and assisted terminal hip flexion in standing, which was not seen in the control group. The augmented muscle activity seen in the FAIS group was theorised to reflect the role of iliocapsularis in contributing to capsule retraction as the hip moves towards a position of impingement.

Although several studies reported pain during strength assessment (Casartelli, et al., 2011; Diamond et al., 2017; Harris-Hayes et al., 2014; Kierkegaard et al., 2017), no correlation has been found between self-reported pain and MVC (Diamond et al., 2017; Kierkegaard et al., 2017) and only angle of peak IR torque appeared to correlate with patients' symptoms (Diamond et al., 2017).

Most studies looking at strength assessment in FAIS used a hand-held dynamometer (HHD) to collect data. Kierkegaard et al., (2017) employed motor-driven dynamometry and Casartelli et al., (2011) used both. Both methods are reported as reliable for hip muscle strength assessment, however, HHD has high inter-observer error and depends on consistency of the assessor (Mayne et al., 2017). Most studies minimised this risk by employing a single assessor for data collection and Mendis et al., (2014) used an external fixation device which demonstrated high intrarater reliability (ICC 0.95, CI 0.82-0.99, SEM 0.8kg).

In a cohort of 74 adolescent male ice hockey players, no significant difference in hip muscle strength was found between players with FAIS, those with asymptomatic morphology and control athletes (Brunner et al., 2016). These findings contradicted the work of Casartelli et al., (2011), Diamond et al., (2016) and Kierkegaard et al., (2017), however, the study populations were different with respect to age, sex, activity level and stage of progression of pathology. Another study with a large cohort of 426 asymptomatic football players found no correlation between strength measurements and cam morphology, but there was an association between pincer morphology and an increase in abduction strength and a lower adduction: abduction ratio (Mosler, Agricola, et al., 2018).

Only one study (Freke et al., 2018), appears to have investigated trunk muscle strength in individuals with FAIS. They found trunk muscle endurance, assessed by a side bridge, to be reduced in pre-surgical hip-arthroscopy candidates. This may have implications in the development of HRP. The abdominal musculature is known to play a synergistic role with the hip muscles in stabilising and mobilising the pelvis (Neumann, 2010) which as discussed in section 2.3.3 has a role in FAIS. As such, this potentially warrants further exploration.

Although FAIS would appear to be accompanied by weakness in the hip musculature, it is unclear at this stage whether muscular function, including strength and neuromuscular activation patterns, are a precursor to a symptomatic state. Future studies are required involving participants with asymptomatic FAI-morphology, looking at the varying sub-types of morphology, with a more homogenous population, to understand the role of muscle weakness in the prevention and management of FAIS.

2.3.5 Gait

Twelve studies, with 396 participants, reported kinetic and kinematic data during walking gait in subjects with FAIS or equivalent. Seven of these studies enrolled pre-surgical candidates. Only one study of small sample size (n = 16) (Peterson et al., 2011) examined running kinetics or kinematics which is a limitation as it could be suggested that walking may not be a provocative enough activity to identify subtle biomechanical changes in the athletic population. They identified reduced hip flexion and anterior tilt during stance phase and hypothesised this is likely to be a compensatory strategy to avoid positions of pain/impingement. No differences were detected in frontal or transverse planes as predicted.

2.3.5.1 *Spatiotemporal*

Individuals with cam or mixed FAIS, when requested to walk at a self-selected pace, have been shown to walk with comparable walking speeds to control participants with no morphology (Brisson et al., 2013; Diamond et al., 2016; Hetsroni et al., 2015; Kennedy et al., 2009; Rylander et al., 2011; Samaan et al., 2017), and cover a similar distance during a 6-minute walking test (Samaan et al., 2017). One study (Hunt et al., 2013) conflicted with these findings and reported that those with FAIS walked significantly slower than a control population (1.23 ± 0.16m/s v 1.33 ± 0.14m/s, p=0.01). These findings are partly explained by a lower cadence demonstrated by those with FAIS (110.3 ± 8.3 v 116 ± 6.7 steps/minute), however they also included participants with isolated pincer morphology.

2.3.5.2 *Sagittal Plane Hip Joint (HJ) Kinematics*

Several studies have shown a statistically significant reduction in total sagittal hip joint range during walking (Diamond et al, 2016; Brisson et al. 2013; Rylander et al., 2013) in FAIS compared with controls. However, there is little consistency in how this motion is lost with some reporting non-significant (Brisson et al., 2013; Lewis, Khuu, et al., 2018) and statistically significant (Hunt et al., 2013; Kennedy et al., 2009) reduction in peak extension angles whereas other studies have found significant (Rylander et al., 2013) and non-significant (Diamond et al., 2016; Hetsroni et al 2015) reduction in peak hip flexion angles. King et al., (2018) also found there to be a reduction in total sagittal range when comparing the symptomatic leg of HRP patients with the asymptomatic limb although this was non-significant (41.9 ± 6.2°, 44.6 ± 2.6°). The asymmetry seen was due to a significant reduction in peak hip extension angle ($p = 0.01$) despite no differences in isolated hip strength or presence of morphology. Lewis et al., (2018) reported sex specific differences during gait, with males demonstrating a bilateral reduction in peak hip extension compared with asymptomatic males, whereas females displayed a reduction in peak hip extension in the painful limb compared with the contralateral limb. Walking with decreased hip extension has been postulated to decrease anterior hip joint forces thereby reducing pain (Lewis et al., 2010), however persistent strategies such as this, whether an adaptation or contributing factor, may ultimately exacerbate symptoms as a consequence of disuse atrophy. The ranges of hip flexion achieved during the gait cycle are not comparable with typical flexion ranges for an FAIS patient (111 ± 18° passive flexion) (Philippon et al., 2007), therefore, any reported reduction in joint range in this direction cannot be directly attributed to the impingement morphology but may instead be a consequence of reduced demand or capabilities of the posterior hip muscles.

2.3.5.3 *Frontal Plane HJ Kinematics*

Nine studies reported frontal plane kinematics for the hip joint. Three studies noted a statistically significant reduction in total frontal range and lower peak abduction angle (Brisson et al., 2013; Kennedy et al., 2009; Rylander et al., 2013), Diamond et al (2016) found similar pattern although their findings were not statistically significant (total frontal range of motion $p = 0.19$, Maximum Abduction p = 0.14). These findings were supported by the work of

Hetsroni et al., (2015) who also reported a significant reduction in hip abduction at heel strike (0.5 ± 2.6° v 2.8 ± 2.7°, *p*=0.01). The one study which included participants with pincer FAIS as well as cam FAIS, showed a significant reduction in adduction (4.1 ± 3.7° v 5.7 ± 2.9 °, *p* = 0.03)(Hunt et al., 2013) which will reduce hip joint contact (Wesseling et al., 2015). No study with isolated cam or mixed FAI morphology supported these findings. One study reported sex specific differences in gait with only females with FAIS demonstrating alterations in frontal plane kinematics. These differences were significant when compared with the asymptomatic contralateral limb (Lewis et al., 2018). There was a trend towards a reduction in adduction of the symptomatic limb in those with HGP in the study by King et al., (2018) independent of the presence of cam or pincer morphology. The findings of King et al., (2018) also didn't coincide with their strength assessment findings raising further questions as to whether biomechanical alterations are a compensatory strategy or a predisposition towards the syndrome.

2.3.5.4 *Transverse Plane HJ Kinematics*

Rylander et al., (2013) was the only study to report a reduction in total transverse plane range of motion (11.3 ± 3.5° v 14 ± 4.4°, p = 0.05) and a reduction in peak internal rotation (IR) (6.5 ± 4.6° v 11 ± 5.4°, *p*= 0.012). A reduction in maximum IR was also reported by Hunt et al., (2013) (*p* = 0.02) with a consequent, non-significant, increase in peak external rotation during the stance phase. A similar, but non-significant, reversal in rotation pattern was also reported by Brisson et al., (2013) in pre-operative FAIS patients verses control subjects. These findings may be a consequence of participants avoiding positions of relative impingement.

2.3.5.5 *Pelvic Kinematics*

Data relating to pelvic kinematics during the gait cycle is also conflicting with 2 studies reporting no differences in tilt (Brisson et al., 2013; Rylander et al., 2013), rotation (Brisson et al., 2013; Rylander et al., 2013), or obliquity (Brisson et al., 2013) whereas Hetsroni et al., (2015) reported an increase in total pelvic tilt (*p* = 0.01, effect size = 0.81) and a reduction in pelvic rotation (*p* =0.04, effect size = 0.7) at heel strike. Lewis et al., (2018) also found an increase in anterior pelvic tilt with a reduction in posterior pelvic tilt but only in the male participants, regardless of whether walking speed was self-selected or prescribed. Kennedy et al., (2009) also found less pelvic obliquity at the start of the stance phase and at toe off (*p* =0.004) which coincided with a reduction in peak hip abduction and total frontal hip range (*p* =0.004). Both these mechanisms are known to decrease hip joint contact forces (Wesseling et al, 2015) and may reflect a different hip-trunk stabilisation strategy by reducing demand placed on the abductor muscles. More in-depth research is required to better understand this.

2.3.5.6 *Hip Joint Moments*

External hip joint moments have been reported to be reduced into flexion (Hunt et al., 2015), adduction (King et al., 2018), and external rotation (Hunt et al., 2015) in hip and groin pain patients during the gait cycle. The changes seen in frontal and sagittal plane moments are known to decrease hip joint contact forces (Wesseling et al., 2015), and in FAIS subjects, may be a consequence of adaptive gait strategies to avoid pain and/or to reduce the demand on the hip extensor and abductor muscles. Contrary to these findings, Diamond et al (2016) and Rylander et al., (2013) reported no difference in hip joint moment between FAIS verses controls and Samaan et al., (2017) found an increase in hip flexion moment impulse during the stance phase inferring higher hip joint loading over a longer temporal period. The latter study found that an increase in hip flexion impulse significantly correlated with increased pain, reduced ADLs, and an increase in severity of acetabular cartilage abnormalities, whether this is the cause, or the consequence is unclear. Individuals with other intra-articular hip joint pathologies such as with OA present with decreased sagittal and frontal plane moments (Diamond et al., 2018) however sub-group analysis reveals that those with advanced OA underload the hip joint, whereas those with milder forms of the disease, not waiting for surgical intervention, are reported to have comparable hip joint moments to healthy controls (Diamond et al., 2018). These findings may reflect the variation in hip joint moments reported in those with FAIS inferring that degree of biomechanical variation may coincide with the stage of pathology.

2.3.5.7 *Surgery*

It has been demonstrated that lower limb gait biomechanics in cam-type FAIS patients, do not return to normal following an open (or combined) surgical procedure (Brisson et al., 2013) with both sagittal and frontal range of motion remaining reduced post-surgery. This potentially strengthens the case that the osseous deformity in isolation may not be solely accountable for the spectrum of issues seen in FAIS. However, as open surgery requires splitting on the gluteus maximus and sometimes the release of the reflected head of Rectus Femoris, muscles which contribute to both motion and stability of the hip joint, the procedure, and the following recovery/rehabilitation period, may itself contribute to the biomechanical deficiencies seen in this study (Brisson et al., 2013). This may also explain the difference seen, albeit non-significant, in peak knee extension moment seen between the post-operative and the control group. Another limitation of this study was the large variation in the timeframes in which post-operation assessment was completed (10-32 months) in these participants. Other studies which included isolated and mixed FAIS morphology have shown positive improvements in hip kinematics while walking following arthroscopic joint preserving surgery (Rylander et al., 2013; Rylander et al., 2011). The heterogeneity of these studies again makes it difficult to ascertain the balance of involvement between underlying morphology and other contributing factors.

2.3.5.8 *Other*

The coordination of the deep hip joint rotator muscles, namely Obturator Internus and Quadratus Internus, has also been shown to be altered during the early swing phase of gait in pre-operative FAIS candidates (Diamond et al., 2017). Both known to be external hip rotators and joint stabilisers (Neumann, 2010), those with FAIS demonstrated less variability in muscle coordination sequencing compared with controls subjects. This may be protective as the hip moves towards a position of relative impingement, however, duration of symptoms varied from 5-48 months in this cohort which introduces an element of bias as a consequence of varying degrees muscular inhibition or atrophy. The pericapsular muscles are also thought to contribute to joint stability (Walters et al., 2014). Although an increase in muscle activity has been seen in iliacus, iliocapsularis and the anterior fibres of gluteus minimus in late stance phase of gait, no difference was seen between footballers with FAIS and matched controls (Lawrenson et al., 2020). The same group found differences in gluteus maximus activity during mid-stance in footballers with hip-related pain compared with asymptomatic controls in a pattern comparable to that seen in those with OA (Lawrenson et al., 2019).

Samaan et al., (2017) found an increase in peak ankle dorsiflexion moments (*p* = 0.04) and ankle dorsiflexion moment impulses (*p* = 0.01) and a trend towards increased knee extension moment (*p* = 0.06) when compared with control participants. Gastrocnemius and soleus muscles are known to contribute to both support and propulsion during running mechanics (Hamner et al., 2010), it is therefore reasonable to hypothesise that the calf complex takes an increased compensatory role when walking to offload the hip joint in those with FAIS. Hindfoot mechanics are also shown to be different in males with cam FAIS, demonstrating excessive inversion at heel strike and a reduction in eversion during stance (Hetsroni et al., 2015). Both articles highlight the potential distal compensations which may occur to optimise function, such as maintenance of walking speed as is demonstrated in both studies, in the presence of pain and aberrant function around the hip joint. It is worth considering in those with more advanced pathology, or when rehabilitating post-operatively, the need to optimise the full kinetic chain to optimise loading around the hip joint.

2.3.6 Squat

Squat based movement patterns are a common component of many sporting activities. It is therefore reasonable to assume that activities which involve high repetitions or high loading into ‘typical’ impingement positions may contribute to the development of pathology in the presence of morphology, and/or such movement patterns may become impaired once painful pathology is present. Seven papers, with a total of 218 participants, have investigated three-dimensional analysis of squat biomechanics in those with cam ± mixed morphology FAIS (Bagwell, Fukuda, et al., 2016; Catelli et al., 2018; Diamond et al., 2017; Lamontagne et al., 2011; Lamontagne et al., 2009; Malloy, Neumann, et al., 2019; Ng et al., 2015). Of these participants, 97 subjects had FAIS. Ng et al., (2015) was the only study to look solely at males and to compare FAIS verses asymptomatic FAI verses control (participants 12, 17, 14 respectively). All bar two papers specified FAIS inclusion criteria as an alpha angle >50.5°, whereas Diamond et al., (2017) and Malloy et al., (2019) included those with an alpha angle of >55°. It has been proposed that a 60° threshold for alpha angles is employed to distinguish normal hip from those with morphology (Agricola et al., 2014) as below this angle does not differentiate between symptomatic and asymptomatic cam-morphology (Sutter et al., 2012) which may lead to inconclusive findings between these papers.

It has been shown in FAIS patients with severe cam morphology (alpha angle of 73 & 83°), that maximum shear stresses on the anterior superior acetabulum when squatting are significantly higher for patients compared to healthy controls (Ng et al., 2012) which may justify why several studies (Lamontagne et al., 2009; Ng et al., 2015; Bagwell et al., 2016; Diamond et al., 2017; Catelli et al., 2018) have shown squat depth to be diminished in FAIS subjects compared with controls. Lamontagne et al., (2009) found no corresponding difference in hip joint range of motion to explain this whereas other studies reported a reduction in peak hip internal rotation (Bagwell et al., 2016) and adduction (Kumar et al., 2014; Diamond et al., 2017). Ng et al., (2015) did not report hip joint kinematics, they were however one of only two studies to compare FAIS versus asymptomatic FAI versus a control group. Although a difference in squat depth was reported between each FAIS, asymptomatic FAI and the control group, the participants in the asymptomatic-FAI and control groups reported no difference in pelvic rotation. Whereas in the study by Cartelli et al., (2018), those with FAIS were shown to have less pelvic motion compared with both controls and those with asymptomatic-FAI. Two further studies reported a loss of sagittal pelvic motion, with a reduction in posterior pelvic tilt in FAIS patients while squatting (Lamontagne et al., 2009; Bagwell et al., 2016). Bagwell et al., (2016b) coupled this with a reduction in mean hip extensor moment, and Casartelli et al., (2018) with a reduction in hip extensor strength, demonstrating a possible reduction in hip extensor muscle activity with resultant increase in dynamic anterior tilt and impingement position. Sagittal plane pelvic and transverse plane hip kinematics are known to be coupled in the healthy population (Bagwell, Fukuda, et al., 2016), therefore the role of acetabular motion on the femoral head warrants further investigation as it may provide further evidence into the distinguishing features between those who with symptomatic morphology versus asymptomatic individuals. Although Malloy et al., (2019) reported no difference in hip joint kinetics, kinematics or maximum squat depth achieved in a young cohort (average age 28 ± 7 years), they did report slower squat cycle duration because of both slower ascent and descent speed. There are several factors which may have brought about this change, such as fear and/or anticipation of pain provocation (Tucker et al., 2012), or the implementation of strategies which lower internal joint moments and reduce in hip joint loading, in turn limiting impingement positions.

Diamond et al., (2017) was the only paper to compare an unconstrained versus and constrained squat: maintenance of an upright trunk, descending parallel to a vertical pole. They were also the only study to consider the potential negative influence of limited ankle range of motion on squat mechanics by using a 30° wedge under the foot. The difference reported was 40.6 ± 11.7% of leg length versus 50 ± 17.8% during the constrained squat, and 25.1 ± 9.7% and 29.7 ± 6.7% during the unconstrained squat (FAI group versus control group in both cases). Although these findings were not reported to be significant, the differences shown may be clinically meaningful, particularly in the elite sport setting, where squat patterns can be a key performance determinant. The FAIS cohort in this study demonstrated a large variation in squat strategies when the squat task was unconstrained with only a significant reduction in ascent speed and a reduction in hip flexion moment reported. There were no other significant differences in hip joint kinematic and kinetic data compared with controls during this task. Once the squat became constrained, FAIS participants demonstrated greater ipsilateral pelvic rise, an increase in hip adduction and a reduction in maximum external rotation moment, all of which may evoke movement towards a position of impingement. This starts to provide some insight into the potential compensatory mechanisms that may be adopted by those with dysfunction hip motion which has consequences for more constrained athletic tasks with high repetitions such as rowing and cycling where ability to adapt is restricted.

Squat depth has been shown to increase following corrective surgery for cam morphology however, the improvements seen are not a consequence of hip range. Lamontagne et al., (2011) found no difference in 3-dimentional hip kinematics when comparing pre-and post-operative data but showed that the increase in mean squat depth was a consequence of knee flexion and ankle dorsiflexion angles. This again leads us to question whether isolated or functional restrictions can purely be attributed to bony morphology. Although not significant, post operatively, patients demonstrated a reduction in anterior tilt which may have reduced femoral-head coverage and consequently reduced the impingement position. It is unclear if this change, and resultant change in squat depth, is an outcome of increased pelvic mobility, or optimisation of the muscular system as a direct consequence of the surgery or its following convalescence and rehabilitation. A limitation of this study is the vast variability in time scale that post-operative assessment was completed (duration 8 to 32 months).

Only one study (Lawrenson et al., 2020) considered muscle activity during squatting between recreational footballers with and without FAIS. No difference in muscle activity was recorded in iliocapsularis, iliacus and anterior gluteus minimus, using fine-wire EMG, or in rectus femoris using surface EMG. As neither pain provocation nor joint kinematics were reported in this study, it is difficult to clearly explain the findings seen.

2.3.7 Stairs

Most literature looking at the biomechanical impact of FAIS has considered low level tasks such as walking and body-weight squatting. However, to ascertain causation or consequence of FAIS in high level sporting populations, more demanding tasks and athletic movements need to be considered to further understand the role of the full musculoskeletal system.

Ascending or descending stairs is a functional, unilateral, task which may begin to answer some of these questions. Limited studies have investigated biomechanical variables ascending stairs (Hammond et al., 2017; Rylander et al., 2013), during a step-up (Diamond et al., 2018) and a step-down task (Harris-Hayes et al., 2020; Lewis, Loverro, et al., 2018). Only Hammond et al., (2017) found those with FAIS ascended more slowly compared with controls ($p = 0.03$).

Hammond et al., (2017), found an increase in hip joint flexion in FAIS participants compared with controls, when ascending 2-steps. This was associated with significantly greater forward trunk lean ($p = 0.01$, effect size = 0.99) which is seen as a strategy to improve mechanical efficiency by aiding forward propulsion (Bouffard et al., 2011) and is supported by the increase in hip flexion moment reported (effect size = 0.94). The same trunk kinematics were not seen in the study by Diamond et al., (2018) however as their study involved a single step, therefore the same degree of forward propulsion may not have been required. This FAIS cohort demonstrated more lateral trunk lean towards the affected hip during the single-leg support phase, potentially reducing the demand placed upon the hip abductors and avoiding pain provocation positions a strategy which is also seen during stair climbing in those with hip OA (Meyer et al., 2016). Diamond et al., (2018) also reported a reduction in relative hip abduction at foot contact in FAIS participants compared with morphology free controls and a reduced peak external rotation moment which may infer a deficiency in the hip abductor muscle group in those with pathology. This reduction in external rotation moment is seen in other intra-articular hip pathologies when stair climbing (Hall et al., 2017) but was not reported by the other studies here.

Another finding by Hammond et al., (2017) was a decrease in peak knee joint flexion moment. A study which examined kinetics and kinematics during sit-to-stand (STS) task, found FAIS subjects when compared with healthy controls, also demonstrated a significantly reduced knee joint contribution during the total support moment as well as requiring more time to complete the task (Samaan et al., 2017). It is unclear in either of these studies as to what the cause-effect relationship is between the knee effort in this cohort. Both coincide with an increase effort, and therefore presumed loading, around the hip joint, which would be undesirable in a cohort with intra-articular hip pathology. This could also be a consequence of generalised lower limb deconditioning in an injured population, or due to inhibition of the rectus femoris muscle which is believed to contribute to femoral head stability, due to its direct attachment to the anterior hip joint capsule (Walters et al., 2014). It has already been shown however that neither activation (Casartelli et al., 2011) or contraction time (Seijas et al., 2016) of this particular muscle is affected in the FAIS population which was reflected in the EMG data collected by both Hammond et al., (2017) and Lawrenson et al., (2020).

Pre-operatively, during a 3-step ascent, Rylander et al., (2013) reported a reduction in total sagittal plan range of motion as a consequence of loss of hip extension and a reduction in maximum internal rotation range. In this study, post-operatively, hip kinematics were restored to normal during walking but not for stair climbing. Participants in this study underwent a variety of procedures including labral repair, partial labrectomy, micro-fracture and acetabular bone resection. It is therefore unclear whether the residual alterations in biomechanics are a consequence of the remaining pathology (9 patients had cam morphology which were not addressed), the consequence of undergoing a surgical procedure, or whether the more physically demanding task of stair climbing places greater demands on the musculoskeletal system, and potentially highlights the deficiencies in this area. This therefore raises more questions for the athletic population in understanding causation behind symptoms of FAIS.

A variety of pelvic motions are reported in FAIS subjects during step ascent when compared to healthy controls, including significant increases in maximum anterior tilt (Rylander et al., 2013), transverse pelvic rotation (Rylander et al., 2013) and obliquity (Hammond et al., 2017; Diamond et al., 2018). Increases in pelvic rotation and obliquity may occur to compensate for reductions in hip range of motion or to offload pathological structures but may in turn lead to other issues around the pelvis and lumbar spine and therefore should be further investigated. Interestingly, although a study with a small sample size, Diamond et al., (2018) reported differing compensation strategies within the FAIS group. Individuals who had significant and concurrent ipsilateral trunk lean and pelvic obliquity, tended to report pain, whereas those participants who had a large lateral trunk lean without pelvic obliquity did not. This may reflect the increased impingement position created at the hip joint as a result of ipsilateral pelvic rise. Those participants who had no lean but increased pelvic obliquity, maintained a painful more externally rotated hip throughout which may contradict this theory.

A limitation of the aforementioned studies is that they used different protocols involving different step heights ranging from 18 to 24 cm high which may explain the variation in results found. In a healthy population, ascending steps requires both femoral elevation, posterior pelvic tilt and pelvic rotation, each of which linearly increase with increasing step height (Bohannon & Smutnick, 2010). This may explain why the study with the lowest step height reported a significant increase in anterior pelvic tilt (Rylander et al., 2013) whereas the study with the highest step (Diamond et al., 2018) reported a non-significant although clinically relevant difference in anterior tilt.

During a step-down task, individuals with FAIS have been shown to have greater degree of hip flexion (4.9°, 95% CI: 0.5-9.2) and increased anterior pelvic tilt (4.1°, 95% CI: 0.9-7.3) than controls (Lewis, Loverro, et al., 2018). As both hip flexion and anterior pelvic tilt are known positions of impingement, this may contribute to the presence of pain and/or progression of pathology in the presence of bony morphology. The degree of hip flexion range reported was a consequence of pelvic position as femoral angles were comparable between both participants and controls. Changes in pelvic position may be accounted for by morphology, neuromuscular strength, length, control, or joint mobility, these were not investigated in this study. When considering those with HRP, Harris-Hayes et al., (2020) did not find differences in hip joint kinematics when performing a step-down task but did find smaller peak hip flexion angles during a single-leg squat. This was found to have an association with reduced hip abductor strength ($r = 0.47$, $P \leq .01$). Single-leg squat has been shown to amplify kinematic and kinematic variables in people with FAIS that are not detected during a double-leg squat task (Malloy, Neumann, et al., 2019). Interestingly this includes smaller peak hip flexion and adduction, smaller peak hip abduction and extension joint moments and slower velocities. These strategies may reflect attempts to minimise hip joint loading and avoid positions of impingement which may provoke symptoms.

When taking into consideration sex, Lewis et al., (2018) found females, with or without FAIS, had greater hip flexion, hip adduction, anterior pelvic tilt and pelvic drop, than males with or without FAIS supporting previous work identifying sex differences between males and females when performing single-leg squat tasks (Weeks et al., 2015; Willson et al., 2006). The sex differences were more evident in the FAIS group than the control group (Lewis, Loverro, et al., 2018), this finding highlights the potential need for differing, sex specific, strategies in the management of FAIS. A limiting factor in two of the studies (Hammond et al., 2017; Lewis, Loverro, et al., 2018) was that asymptomatic individuals did not undergo radiological assessment. It is therefore unclear if the control groups included those individuals with asymptomatic morphology. Whereas Harris-Hayes et al., (2020) showed no differences in measures of bony morphology among patients with HRP compared with controls. Further research comparing the 3 sub-groups may help in understanding what factors contribute to the development of FAIS in those with morphology.

2.3.8 Single leg Drop Jump/Landing

King et al, (2018) reported a significant asymmetry in sagittal hip joint kinematics during a single leg drop jump (SLDJ) task when comparing HRP with the contralateral asymptomatic limb in sub-elite footballers (42.4 ± 11.8° v 46.9 ± 14.1°, *p* = 0.04, moderate effect size). The majority of this asymmetry resulted from a larger degree of hip flexion at toe-off which may be compensatory to reduce anterior joint through limiting hip extension range (Lewis et al., 2010). They also reported inconsistent biomechanical patterns in peak hip flexion and the frontal plane. Both symptomatic and asymptomatic hip joints in this group were reported to have a similar presence of cam ± pincer morphology, reinforcing the belief that osseous structure alone may not be responsible for FAIS symptoms. Only one other, low quality study, examined SLDJ in individuals FAIS (Kumar et al., 2014), no kinetic or kinematic differences were noted in this study other than subjects with FAIS landed with their feet closer together (0.3 ± 0.05m; 0.37 ± 0.04m, *p* = 0.29). As this would draw the hip joint towards a position of impingement and increase hip joint contact forces, this may contribute toward FAIS.

When considering a single leg drop landing (SLDL) in individuals with long standing groin pain (> 3 months), the sagittal plane differences seen during SLDJ were not supported by Janse van Rensburg et al., (2017). This cohort demonstrated an increase in hip abduction (2.05°, *p* < 0.001, r = 0.49), hip external rotation (0.86°, *p* = 0.03, r = 0.29) and downward lateral pelvic tilt (0.77°, *p* = 0.01, r = 0.35) at initial ground contact and an increase in pelvic internal rotation (1.06°, *p* = 0.02, r = 0.30) at lowest vertical position compared with pain free controls. The differences reported in hip joint kinematics between the King et al., (2018) and Janse van Rensburg et al., (2017) trials are not unsurprising due to the differing forces produced when landing and rebounding. There were also other methodological differences such as classification of groin pain patients and the height of the step used: participants in the King et al., (2018) took off from a 30cm step compared with a 20cm step utilised by Janse van Rensburg et al., (2017). It is known that jumping from a greater height is coupled with increased ground reaction forces on landing (Newton et al., 2001) which places greater demands on the musculoskeletal system.

2.3.9 Balance

The Star Excursion Balance Test (SEBT) has been shown to successfully distinguish between individuals with FAIS and healthy controls, with a 12% and 9% difference in maximum distance reached, relative to leg length, between patients in the posterolateral (PL) and posteromedial (PM) directions respectively (Johansson and Karlsson, 2016). This was supported by the work of Freke et al, (2018) who also reported difference in anterior reach distance in presurgical hip arthroscopy candidates compared with control, but not between limbs. This concurs with previous work which has shown that the SEBT is a valid and reliable measure in the prediction of lower limb injury and the identification of dynamic balance deficits (Gribble, Hertel and Plisky, 2012). Johansson and Karlsson (2016) also reported a significant difference in the PL direction between the symptomatic side and the asymptomatic limb (77.6%, 82.4%, p = 0.005), however, Munro and Herrington, (2010) reported that at least a 6-8% difference was required in order to be classed as a valid and meaningful difference which therefore leads us to question whether the SEBT can sensitively identify between a symptomatic and an asymptomatic limb. The inability to confidently distinguish between limbs may be because the SEBT requires use of both legs and a variety of physical qualities including strength, control, ROM, balance, and co-ordination (Gribble et al., 2012), which as previously identified, are shown to be lacking in those with FAIS.

The SEBT also demonstrates strong correlations between HAGOS sub-scores for pain and symptoms but not for sports and recreation subscales or quality of life when the PL and PM directions are considered. There were also moderate correlations for PL and ADLs and a functional one leg raise test but no correlations between the ‘Hip Sports Activity Scale’ or any assessment anteriorly (Johansson and Karlsson, 2016). The gluteus medius, which is known to dynamically stabilise the hip and contribute to the reduction of hip joint forces (Retchford et al., 2013), is shown to be less active in the PM position of this test (Norris and Trudelle-Jackson, 2011). However, Freke et al., (2018) found 53% of variance in PM reach direction was explained by adduction strength and sex, whereas 46% of PL reach was explained by adduction and internal rotation strength. Abduction and extension strength was shown to be non-significant between group. It may be that posteriorly directed movements are therefore more sensitive components of the SEBT than the anterior ones, as the hip is moving towards a position of impingement which it is not able to control. This provides useful evidence that the SEBT may be a useful component in a wider assessment in the identification of those with FAIS.

Dynamic balance during a single-leg squat task has also been reported to be reduced in those with hip chondropathy >18 months post arthroscopy (Medio-lateral (ML) Range: 3.5 ± 0.77cm v 3.14 ± 0.45cm, $p = 0.023$), but not with a static single-leg balance task with eyes closed (Hatton, Kemp, Brauer, Clark and Crossley, 2014). In this cohort, increased hip external rotation range of movement accounted for 11% of the variance seen in motion in a ML direction during the squatting task which may indicate a greater need for muscular control when there is an associated increased in ROM. As hip chondropathy is an advanced stage of pathology in those with FAIS, further investigation into balance in those with less advanced disease, or indeed those with asymptomatic morphology, is required. This will help in further understanding the cause-effect relationship between dynamic balance and the development of FAIS, which is particularly relevant to performance and injury risk in many athletic populations.

2.4 Conclusion

There is a wealth of literature available relating to biomechanical variations between those with FAIS and healthy controls, however there is a lack of high-quality evidence, and studies are heterogenous with respect to diagnostic criteria, measures used, and the methods of investigation employed. This may explain the inconsistency in study findings. It is apparent that whether factors such as diminished squat depth, muscular weakness or speed of task execution are protective or provocative, they will equally have deleterious effects on performance in the elite sporting population. Greater understanding of these factors may therefore aid in the appropriate identification and management of those with morphology and pathology alike.

The findings of this review suggest that it is unlikely that bone morphology in isolation is accountable for the development of FAIS. Although many correlations between kinetic and kinematic variables have been shown, it is not clear if they are responsible for the onset of symptoms or are a compensation. Of note, alterations or restrictions in pelvic mobility appear to be a consistent finding and distinguishing feature of those with FAIS, this area in particular warrants further attention.

To ascertain a causal relationship between FAI-morphology and other intrinsic predisposing risk factors, more in-depth analysis comparing those with FAIS and those with asymptomatic morphology, as well as healthy controls, is required, through varying phases of maturation, disease progression and differing levels of athleticism. At present, a clear cause-and-effect relationship cannot be made.

2.5 Summary

FAI-morphology is known to be highly prevalent in the athletic population (Frank et al., 2015), yet it is unlikely that this bone morphology in isolation is accountable for the development for FAIS. FAIS can have consequences for both athletic performance and longer-term health. Therefore, the ability to effectively diagnose FAIS, and identify factors which may contribute to the development of a symptomatic state, may aid in both the mitigation of injury risk, as well as improve the longer-term management of the syndrome.

Physical examination is a fundamental component in the diagnosis of FAIS (Griffin et al., 2016). However, limited clinical diagnostic tests have been shown to make a significant change in the post-test probability for FAIS, with only FADDIR impingement test, IR at 90° flexion, and FABERs test showing moderate to high levels of sensitivity but poor levels of specificity.

The narrative review in section 2.3 identified the existence of differences in functional and physical presentations in the presence of FAIS compared with the healthy population. The review confirmed the paucity of literature on this topic specifically in the rowing population. It is proposed that a combination of these functional and non-functional physical traits, in conjunction with sports specific training requirements, may contribute to the development of FAIS. Furthermore, section 2.2 identified that clustering assessments may aid in increasing the accuracy of testing.

Using a battery of physical and biomechanical assessments to profile athletes in high-risk sports such as rowing, may help to identify individual at risk of HRP such as FAIS. This can in turn assist athletes, coaches, and medical practitioners to determine the appropriate injury prevention and management strategies within the constraints of both health and performance requirements.

Reviewing the literature has identified that range of movement, hip strength, balance, and squat patterns are altered in the presence of FAIS. Gait and jumping-landing tasks were also found to be affected, although as rowing is a seated, non-impact sport, these assessments will not be taken forwards. As imaging is not routinely carried out as part of the Great Britain Rowing Team screening practices, the diagnosis of FAIS cannot be made in all instances as presence of image findings is a key diagnostic component (Griffin et al., 2016). As such, for the remainder of the thesis, the terminology of HRP will be used instead of FAIS.

The aim in the subsequent chapters is to explore the association and predictive abilities of the following tests in the development of HRP:

- Hip Internal rotation
- Double-leg squat
- Y-balance assessment
- Single-leg squat
- Hip Abduction strength
- Hip Adduction strength

These assessments are in agreement with the recent research recommendations proposed by the IHiPRN in relation to the standardisation of physical capacity measurement in those with hip-related pain (Mosler et al., 2019).

CHAPTER 3

3 GENERAL METHODS

The systematic and narrative reviews in Chapter 2 identified the existence of differences in functional and physical presentations in individuals with FAIS compared with the healthy population. The review also confirmed the paucity of literature in the rowing population. Assessment of these characteristics will be taken forwards to investigate the association between them and the development of HRP in elite rowers.

This chapter describes the materials and methods used in the experimental chapters to conduct these assessments. Additional, specific, or modified methods are described within the methods section of the relevant study chapters.

3.1 Anthropometry

For each study, stature, body mass and leg length were collected using the following standardised methodology.

3.1.1 Stature

Participants were required to stand vertically, in the anatomical position, facing away from a stadiometer scale (Seca, Hamburg, Germany). The stadiometer arm was lowered until it is rested horizontally on the most superior aspect of the participant’s head. Stature was measured in accordance with International Society for the Advancement of Kinanthropometry (ISAK) procedures and was recorded to the nearest 0.1cm. Due to equipment availability at different locations, a portable stadiometer was used at the EIS High Performance Centre (Bisham Abbey, UK) and a wall mounted stadiometer (both items Seca, Hamburg, Germany) was used at the National Rowing training centre (Sherriff’s Boathouse, Caversham, UK). Stature data was only collected during the initial assessment.

3.1.2 Body Mass

Body mass was recorded using electronic scales (Marsden m-510, Rotherham, UK) which were placed on a hard, level surface and calibrated daily using a known mass. Participants were encouraged to wear either loose fitting or Lycra shorts and sports bras for females. Body mass was recorded to the nearest 0.1 kg prior to the first training session of the day (approximately 07.00-07.30).

3.1.3 Leg Length

Leg length was measured using a standard tape measure as described by Middleton-Duff, George & Batterham (2000). Participants were asked to lie on a treatment table in a relaxed position, with the examiner standing on the same side of the table as the limb being measured. The proximal end of the tape measure was placed on the inferior aspect of the anterior superior iliac spine (ASIS), with the distal end of the tape being placed upon the most prominent aspect of the medial malleolus. The measure was repeated twice to ensure consistency. This method of leg length assessment has been shown to have excellent interrater (ICC 0.99) and intrarater (ICC 0.99) reliability, and excellent validity (ICC 0.98) when compared with radiology (Neelly et al., 2013). Limb length was recorded to the nearest 0.1cm. Data was only collected during the initial assessment.

3.2 Hip Internal Rotation Range of Motion

Hip internal rotation was assessed using the commercially available Easyangle® (EA) (Performance Health, Sutton-in-Ashfield, Nottinghamshire). The EA is a handheld digital goniometer, with a display attached in the middle of a hard plastic ruler. Values are reported in 1° intervals. The assessment was carried out in loose fitted clothing, in order not to restrict the procedure.

Figure 3-1: Hip internal rotation assessment. Figure 3-2: EasyAngle© placement

A two-person technique was employed: one practitioner to move the limb, one practitioner to measure the range of motion. The participant lies supine on a treatment-table with the leg to be assessed at 90 degrees hip and knee flexion. The contralateral leg placed in a neutral hip position; knee extended with a relaxed ankle. The test leg is passively moved into rotation. End range is considered the point at which resistance is felt or the earliest visible movement of the pelvis, indicating movement of the lumbar spine.

The EA goniometer is aligned along the patella apex, along the line of the tibia (Figure 3-1). The range of movement test is repeated three times, and mean score calculated. Both legs are assessed, and participants are asked to report if any pain is produced on assessment. This assessment methodology has previously been shown to have excellent test-retest reliability (ICC 0.95) when using a standard manual goniometer (Nussbaumer et al., 2010).

3.3 Double-leg squat

The body mass double-leg (DL) squat was measured using 2-dimensional (2D) video analysis. Although 3-dimensional (3D) motion capture is deemed 'gold standard' for assessing kinematics, 2D video analysis if often the preferred method due to ease of use in a clinical setting in conjunction with time and financial costs required to use it (Schurr et al., 2017). 2D analysis has been shown to be reliable (Gwynne & Curran, 2014; Herrington et al., 2017; Munro et al., 2012b) and able to produce comparable measures to those achieved during 3D motion capture (Schurr et al., 2017), especially during less complex task when assessing uniplanar movements (Herrington et al., 2017).

A standardised protocol was used (see Figure 3-3): a reference mark (40cm length of zinc oxide tape) was placed 100cm from a calibrated point (a wall). A 50Hz Sony video camera (Sony Handcam, HDR-PJ10, SONY Corporation, Japan) was mounted on a tripod (Sony VCT-R640, SONY Corporation, Japan), 80cm high from the base of the camera lens and the centre of the tripod, 350cm from the reference mark. The camera was levelled using the built-in level on the tripod. The camera was placed perpendicular to the reference mark to ensure that the squat was filmed in the correct plane. Ensuring that the set-up is a fixed distance and perpendicular to the camera, reduced the risk of perspective, or parallax error, which can happen if motion occurs outside of the chosen plane of movement. This could lead to distortion of the video images and inaccuracies in subsequent data analysis (Haven et al., 1977). As the key parameter being assessed, squat depth, is expressed as a relative measure (% of leg length) rather than an absolute, it is not subjected to perspective error.

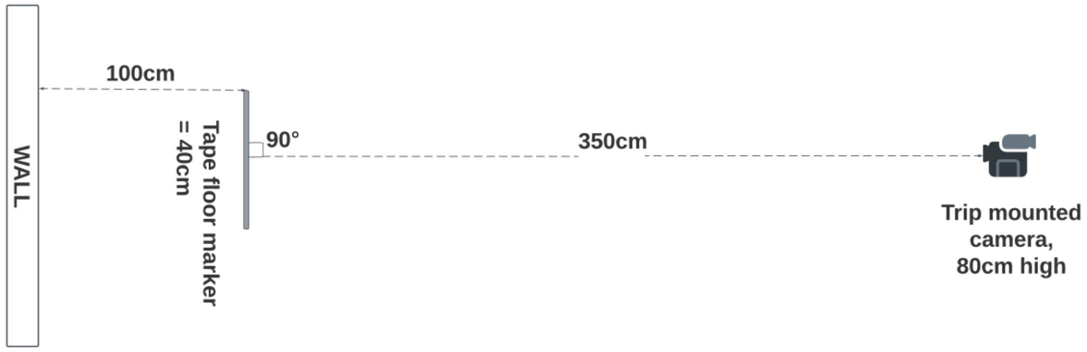


Figure 3-3: Camera set-up protocol

Data was collected at several locations: The National Rowing training centre (Sherriff's Boathouse, Caversham, UK) and EIS High Performance Centre, (Bisham Abbey UK), based on the availability of the participants. Therefore, during the initial assessment at each location, an empty calibration film was recorded in preparation for analysis and a visible landmark measured e.g., the width of a squat rack, the height of a window.

The DL squat was performed with the participants wearing their own training shoes and Lycra shorts. Participants were instructed to wear similar clothing to each subsequent visit. Participants were instructed to stand with their legs shoulder width apart with hands placed across the chest. They were requested to perform three DL squats to their lowest comfortable depth, at a self-selected speed, as if performing a loaded back squat in the weight room. Heels remained in contact with the floor throughout.

Participants repeated the procedure three times to collect footage in both the frontal and sagittal planes. For frontal plane footage, participants stood with their back to the camera and their heels up against the taped reference mark. For sagittal plane, footage was collected from both the left and right sides, with the foot nearest the camera up against the reference tape. The participants were instructed to perform three DL squats in each position therefore performing nine DL squats in total. Randomised block order was employed for starting position to limit the effect that starting position may have. For example: (1) Back (B), Left (L), Right (R); (2) L/R/B; (3) R/B/L etc.

Retrospectively, the video footage was uploaded to Quintic (version 31; Quintic Consultancy Ltd, Coleshill, Birmingham, UK) for analysis. Two key variables were considered: squat depth and squat symmetry. Pelvic, knee and ankle kinematics were also assessed.

3.3.1 Anatomical landmark referencing

Prior to testing, markers were placed on the following landmarks: *Left Anterior Superior Iliac Spine (ASIS), Right ASIS, Left Greater Trochanter, Right Greater Trochanter, Left Posterior Superior Iliac Spine (PSIS), Right PSIS and a vertical marker identifying midline placed over the spinous processes of the third and fourth lumbar vertebrae.* All markers were applied by the lead author (E.J.A). Pre-cut markers were made from kinesiology tape of a contrasting colour to the participants garments. The pre-cut tape was cut to the following sizes:

- 2.5 x 5cm, 2 per person

- 2.5 x 10cm, 2 per person
- 3 x 3cm, 2 per person
- 1 x 5cm, 1 per person

3.3.1.1 *ASIS Marker Locations:*

The greatest prominence of ASIS sits in the centre of the first centimetre of tape; the remaining tape is attached laterally (Figure 3-4).

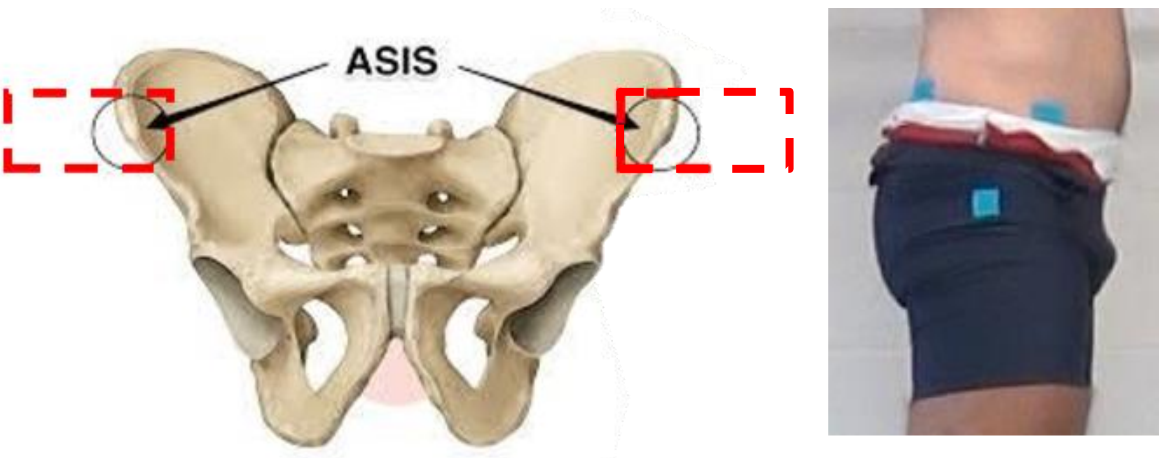


Figure 3-4: ASIS and greater trochanter marker locations

3.3.1.2 *Greater trochanter marker location*

The greatest prominence of the greater trochanter sits in the mid-point of a 3 x 3cm piece of kinesiotape (Figure 3-4). This was the only reference point not attached directly to the skin.

3.3.1.3 *PSIS Marker Location*

To improve accuracy during video analysis, a vertical line is measured and drawn 1cm from the edge of the tape and with a marker pen. This is done during the study preparation phase. The vertical line sits directly over the greatest prominence of the PSIS. The remaining 9cm length sitting laterally (Figure 3-5).

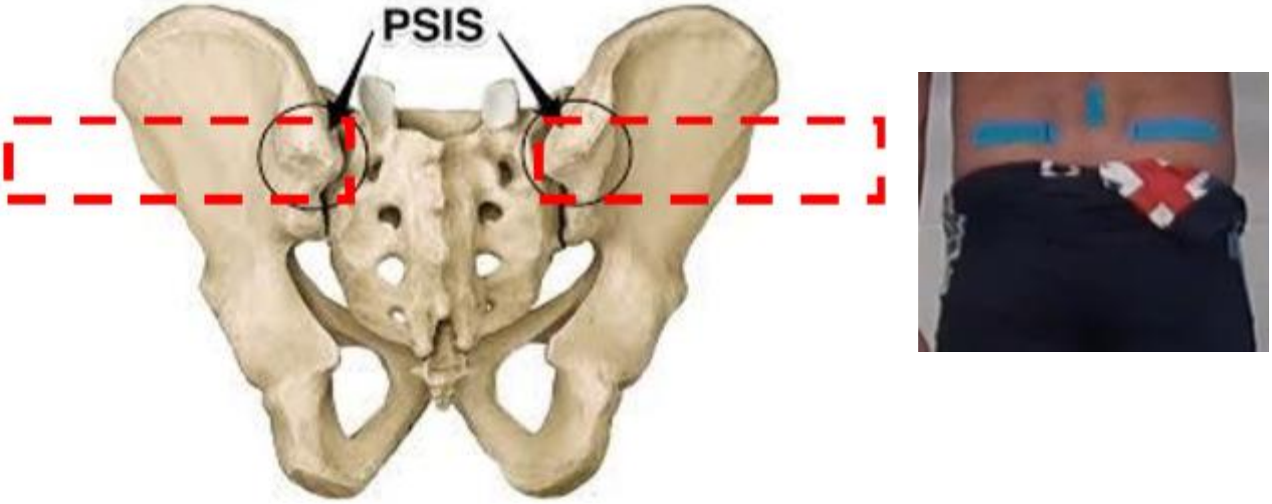


Figure 3-5: PSIS marker location

The landmarks used to measure the angles at the knee and ankle were as follows; knee: greater trochanter, the lateral condyle of the knee; lateral malleolus; ankle: lateral condyle knee, lateral malleolus, horizontal line depicting the floor. Angles were measured in the deepest part of the squat.

During the development of the method, a pilot study was conducted to ascertain the best way to establish frontal plane midline. No difference was found between using the spine as central reference or the mid-point between the heels ($p > 0.05$). Therefore, for ease of analysis, spinal measures were employed.

3.3.2 2D Data Processing

For each trial, two still images were created in the respective plane of movement for analysis. In the frontal plane still images were captured with participants standing fully erect (Figure 3-6A) and at the lowest depth of the squat (Figure 3-6B). Prior to video calibration and analysis, a horizontal reference line was added to demarkate the floor.

Similarly, in the sagittal plane still images were captured with participants stood fully erect (Figure 3-6C) and at the lowest depth of the squat (Figure 3-6D), where the following were added:

- A horizontal reference line to demarkate the floor
- A vertical reference line bisecting the individual using the spine marker as the centre point

The variables measured are presented in Figure 3-6. The following formulae were used to establish the key variables:

Frontal plane squat depth (%) = PSIS distance to floor in squat / PSIS distance to floor in standing

Sagittal plane squat depth (%) = Greater trochanter distance to floor in squat / Greater trochanter distance to floor in standing

Pelvic obliquity (mm) = [(Left PSIS in squat – Right PSIS in squat) – (Left PSIS in standing – Right PSIS in standing)]

Lateral drift (mm) = Right PSIS to vertical marker in squat – Right PSIS to vertical marker in standing

For both frontal and sagittal plane squat depth, “0%” represents the floor, and “100%” prepresents fully erect standing.

For pelvic obliquity, zero indicates a level pelvis with the horizon. A positive number indicates a pelvic drop to the right hand side. A negative number indicates a drop to the left hand side. For lateral drift, zero indicates no lateral movement. A positive number indicates a movement toward the right, a negative number indicates a shift to the left.

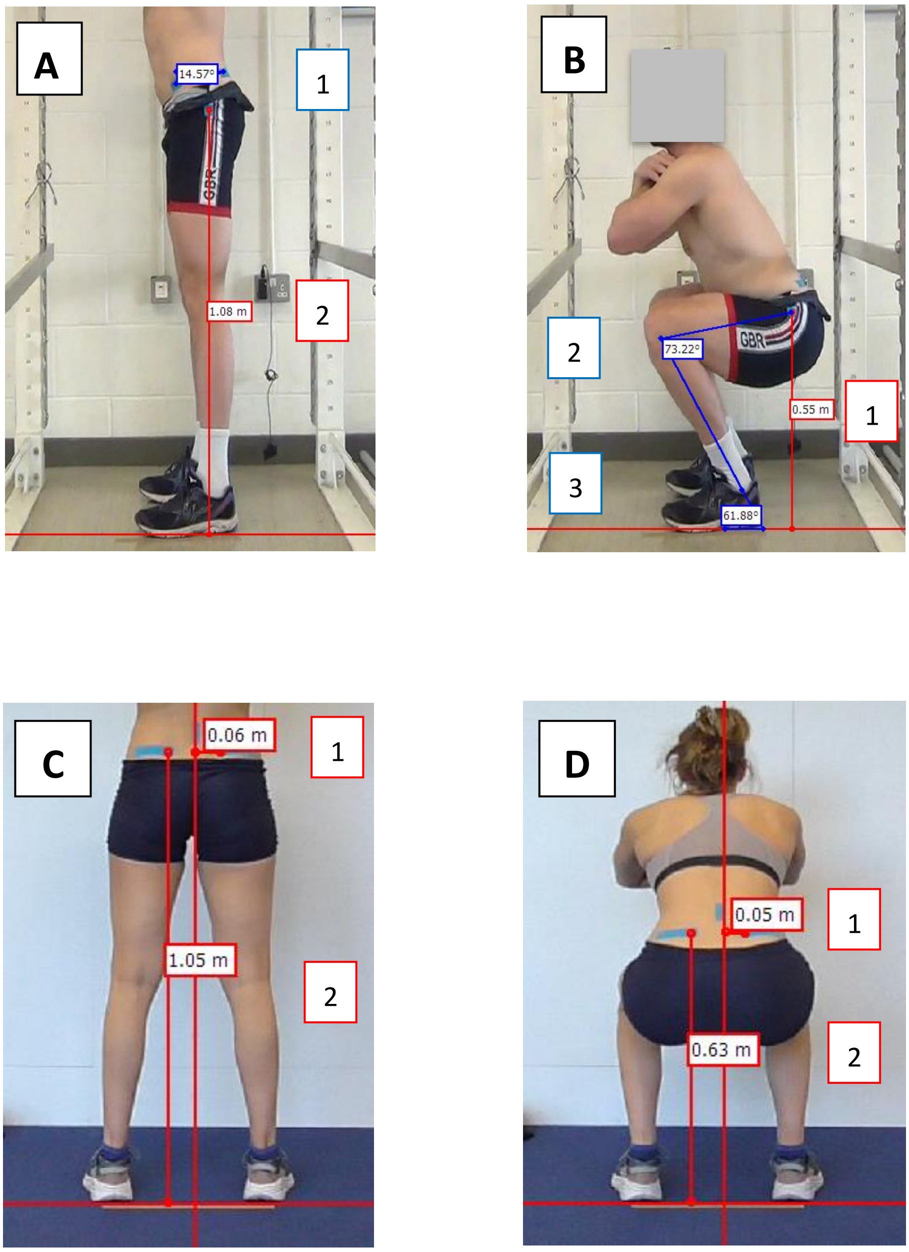


Figure 3-6: Data Processing during double-leg squatting

A1: Pelvic angle in standing (°), left & right; A2: The distance from left/right greater trochanter to floor (m), in standing; B1: The distance from left/right greater trochanter to floor (m), in deepest squat; B2: Knee angle in deepest squat (°), left & right; B3: Ankle angle in deepest squat (°), left & right; C1: The distance from left/right PSIS to central marker line (m) in standing; C2: The distance from left/right PSIS to floor (m), in standing; D1: The distance from left/right PSIS to central marker line (m), in deepest squat; D2: The distance from left/right PSIS to floor (m), in deepest squat.

3.4 Y-Balance Assessment

The Y-balance assessment was conducted using the commercially available Y-balance Test Kit^{TM} (Move2Perform, Evansville, IN, USA). The assessment was carried out in loose fitted clothing, in order not to restrict the procedure, and barefoot to eliminate support provided by footwear.

The participant stood with the big toe of the test leg aligned with the centre grid line. The participant performs a single-leg squat on the weight bearing (WB) test limb, while the foot of the non-WB limb lightly slides the rectangular plastic reach indicator block as far as they are able without losing balance in the specified direction. There are 3 directions: anterior, posterior-medial (PM) and posterior-lateral (PL) (see Figure 3-7). The following standardised instructions were given: *with your hands placed on your hips and maintaining a single-leg stance on the test leg, reach the opposite leg as far as possible in the chosen direction by lightly pushing the side of the indicator box. You may bend your stance leg, but your heel must remain in contact with the floor, and you must not touch down or take load through your non-WB foot.* One of the research team demonstrated the test before the participant had 4 practice tests on each leg, in each direction. This warm-up protocol was employed as maximum excursion distances achieved during a comparable test, the star excursion balance test, have been shown to stabilize following this number of practice trials (Munro & Herrington, 2010; Robinson & Gribble, 2008). For a trial to be successful, the participants hands must remain on their hips and the reach leg cannot provide WB support. The toe of the stance leg must remain in position on the centre grid, the heel must remain in contact and balance is to be maintained through each test repetition. A test was also classed as invalid if the participant ‘kicked’ or ‘nudged’ the sliding box.

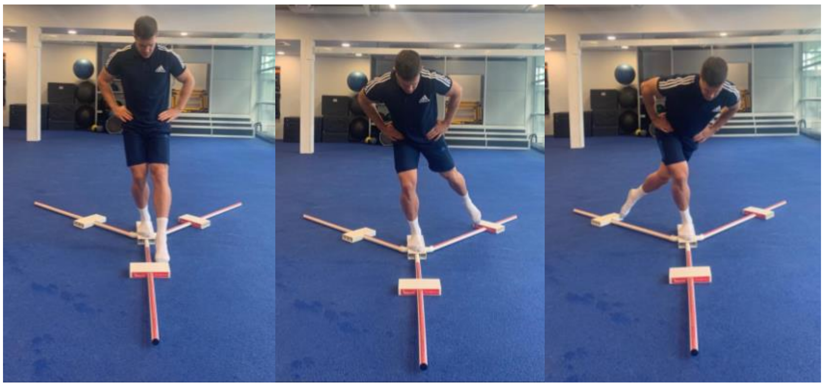


Figure 3-7: Y-balance Test Kit™

Following the warm-up, the participant then self-selected which foot to begin the test with. The test was repeated in the same direction, 3 times or until 3 successful tests had been repeated. This was repeated on both legs in each of the 3 directions. The distance achieved for each test was recorded to the nearest 0.5cm.

Following assessment, normalised excursion distances were calculated by dividing the mean distance reached by the corresponding leg length, multiplied by 100 (P. Gribble et al., 2012).

3.5 Single-leg Squat

Participants were requested to wear standard training shoes and encouraged to wear either loose fitting or Lycra shorts and sports bras for females, or appropriate athletic clothing which would permit visualisation of the trunk and limbs. A single (Sony Handcam, 50Hz, HDR-PJ10, SONY Corporation, Japan) video camera was set up 3.5 m away from a reference mark. Participants were instructed to stand on the mark facing the camera and to perform three single-leg squats (SL squat) to a comfortable depth, with their hands resting down by their sides but not in contact with the body, and the non-weight bearing leg placed behind them (Figure 3-8). Depth of squat was not standardized to reflect clinical practice, which is methodology that has been employed in several studies previously (Crossley et al., 2011; Weeks et al., 2012). The participant performed three practice SL squat prior to filming 3-test SL squat on each side. Participants self-select which leg to begin the test with.

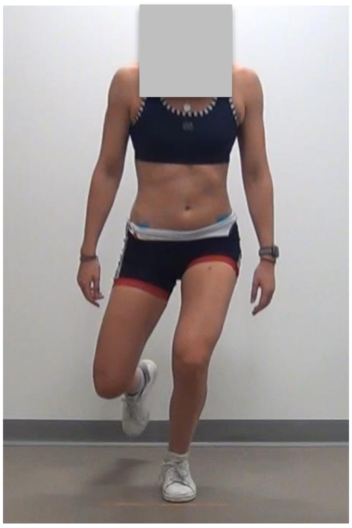


Figure 3-8: Single-leg squat (SLS)

Retrospectively, the video footage was uploaded to Quintic (version 31; Quintic Consultancy Ltd, Coleshill, Birmingham, UK) for analysis using a qualitative, 10-point assessment system as described by Herrington et al., (2013). The assessor watched the videos three times, in real-time speed, recording an average score for the respective scoring components (see Figure 3-9).

	Task: **Single-leg squat** **Single leg step down** **Single leg hop for distance**	**Left**	**Right**
Arm strategy	Excessive arm movements 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 toes (noticeable valgus)		
	Patella pointing past inside of foot (significant valgus)		
Steady stance	Touches down with NWB foot		
	Stance leg wobbles noticeable		
	Total		

Figure 3-9: Qualitative analysis of single-leg loading (QASLS)

3.6 Hip Strength Assessment Protocol

Isometric hip abduction/adduction strength assessments were conducted as recommended by Maffiuletti (2010). This included a standardised warm up of hip mobilisation exercises (see 10.7 Strength assessment warm up). The testing protocol is routine practice within in the Great Britain Rowing Team whereby athletes are profiled 3 to 4 times per season.

The test position selected was a side lying position as this is the procedure currently employed in this specific rowing cohort. It has been used for more than five years for longitudinal data collection and was therefore familiar to the rowers assessed. Although this test position requires the participant to overcome gravity, it has been shown to be the optimal position for force production when compared with standing or supine lying (Widler et al., 2009). The data was not normalised for gravity as both assessments were performed in the same position allowing for comparison. A Lafayette Hand-Held Dynamometer (HHD) unit (Nicholas Manual Muscle Tester, Lafayette, IN, USA) was used for each procedure. A long lever assessment was used which is known to be a more reliable test position than using a short lever (Krause et al., 2007).

For hip strength assessment, a make-test was employed as recommended by Mayne et al. (2017). Make-tests have been shown to have greater reliability than a break-test (Schmidt et al., 2013), although this may depend on tester skill and strength (Stratford & Balsor, 1994). They are also associated with a lower risk of injury (Hébert et al., 2011) which is an important consideration in the athletic population (Reiman & Thorborg, 2014).

To stabilise the participant in side-lying, two soft plyometric boxes were utilised. Both boxes had a width and depth of 90 cm by 75 cm, respectively. Two different box heights were required: 45 cm and 15 cm.

For both hip abduction and hip adduction, the taller 45 cm box was placed against the wall. The shorter 15 cm box was used to stabilise the participant against the 45 cm box (see Figure 3-10). This was fixed in place with a 25kg weight.

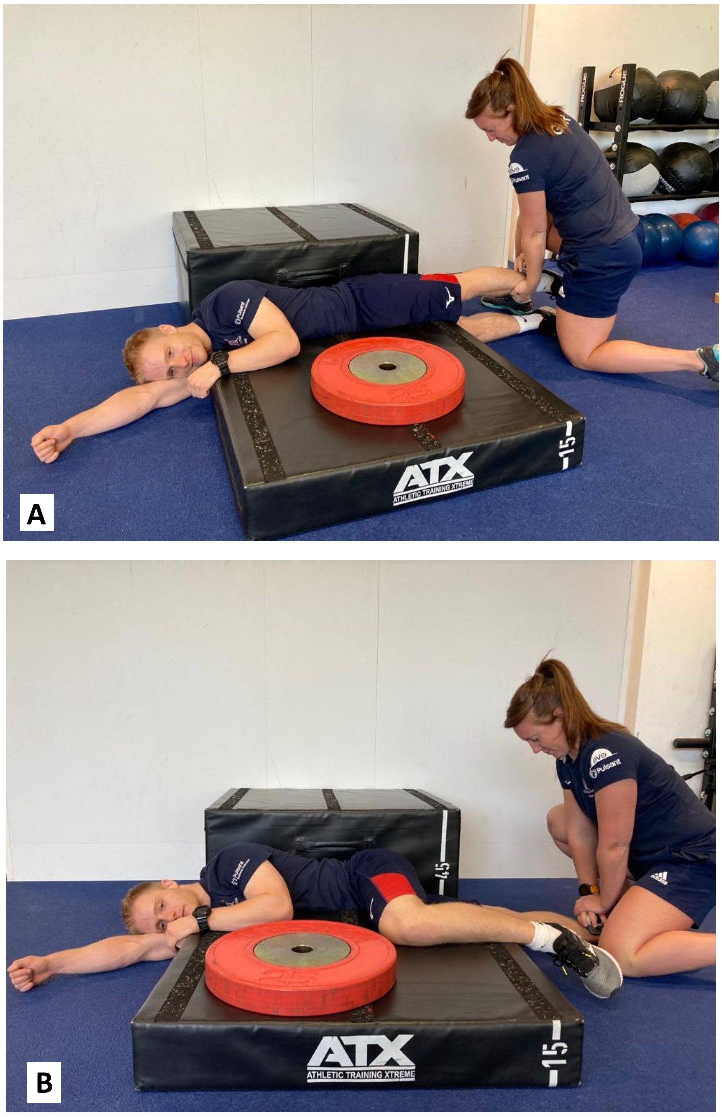


*Figure 3-10: Set up positions for (**A**) Hip Abduction and (**B**) Hip Adduction in side-lying.*

3.6.1 Isometric Hip Abduction

Participants lay on their side with the testing leg upper most, both legs extended and their back firmly against a 45 cm depth plyometric box. The shorter 15 cm soft plyometric box was placed up against the participants chest to stabilise the subject and restrict any rotational movement. This was fixed in place with a 25 kg weight. The underside arm was supporting the participants head, the uppermost arm was placed on top of the box in front of the participant. The tester supported the weight of the top leg in hip joint 0° abduction-adduction. With the free hand, the HHD was placed 2 fingers above the lateral malleolus.

To achieve a maximum voluntary contraction (MVC), participants were instructed to apply pressure upwards into the HHD and to build up force gradually until maximum effort was achieved. This was indicated by the first beep of the HHD. Maximum contraction was sustained for approximately 3 seconds as indicated by a second beep of the HHD.

To record a successful test, the participant must: avoid any sudden kicking motion, maintain a straight leg with no hip motion in any plane, no knee flexion, and no motion through the trunk.

3.6.2 Isometric Hip Adduction

Participants were stabilised between two different height soft plyometric boxes as described previously. The uppermost, non-test leg was bent at the hip 60˚ and knee to 90˚ and rested on top of the shorter plyometric box. The lower test leg was maintained in knee extension with ankle dorsiflexion. The HHD unit was placed two fingers above the medial malleolus.

To achieve an MVC, participants were instructed to apply pressure upwards into the HHD and to build up force gradually until maximum effort was achieved. This was indicated by the first beep of the HHD. Maximum contraction was sustained for approximately 3 seconds as indicated by a second beep of the HHD.

To record a successful test, the participant must: avoid any sudden kicking motion, maintain a straight leg with no hip motion in any plane, no knee flexion, and no motion through the trunk.

For assessment of both abduction and adduction, the following standardised instructions were given:

"Ready, Build, Push. 3, 2, 1".

Participants were asked to inform the tester immediately if any pain was experienced during the assessment. In this instance the assessment was stopped. MVC was measured in Newtons (N) and converted to torque (N/m) using the following formula:

$$N/m = N \times \text{leg length } (m)$$

Mean values across 3 tests were calculated along with standard deviations (SD) and 95% confidence intervals (CI) for both hip abduction and adduction.

CHAPTER 4

4 RELIABILITY STUDIES

The investigation into the association between intrinsic risk factors and hip-related pain (HRP) can only be achieved using reliable, sensitive, and specific assessments (Wilson & Jungner, 1968). Assessment of reliability is a necessary requirement in the development of a screening tool (Wilson & Jungner, 1968) to understand test consistency and repeatability in relation to the test, tester and/or the measurement tool itself (Batterham & George, 2003). Reliability allows for identification of systemic bias and measurement error, which enables interpretation of assessment accuracy (Batterham & George, 2003).

The following chapter will assess the reliability of the five key assessments that will be used for the remainder of the thesis.

4.1 Hip internal rotation range of motion reliability

Decreased hip joint range of movement (ROM) is a common finding in patients with hip pathology. Restrictions in internal rotation (IR) are predictive of conditions such as osteoarthritis (OA) (Birrell et al., 2001; Damen et al., 2019), FAIS (Griffin et al., 2016), chondrolabral pathology (Kemp et al., 2014) as well as being a key prognostic in distinguishing HRP in athletes (Mosler et al., 2015). Accurate assessment is therefore an important component of the clinical examination of patients with hip joint-related pain.

Internal rotation, with and without symptom provocation can be a useful screening tool. When assessed in 90° hip flexion, IR has been shown to have moderate-high sensitivity (50-98%) with conflicting findings for specificity (4-96%) when used as a pain provocation test for HRP. This is discussed in more detail in section 2.2.

Several studies have reported a correlation between IR ROM with presence of cam morphology as indicated via alpha angle (Kapron et al., 2012; Mosler, Agricola, et al., 2018; Wyss et al., 2007; Yuan et al., 2013). In adolescent athletes, three studies have found associations between restricted IR and evidence of asymptomatic hip pathology (Wyles et al., 2017; Yuan et al., 2013) and when comparing a symptomatic verses non-symptomatic limb (Sink et al., 2008). It has also been shown to have a strong negative correlation with the size of cam morphology when considering the rowing population (Wedatilake et al., 2021). Other work has refuted the association of IR with bony anatomy, reporting similar restrictions in hip IR, regardless of presence of cam morphology (Murphy et al., 2017; Tak et al., 2016).

Assessment of IR is a commonly used component of musculoskeletal screening tools in sports to assess for risk of HRP. Tak et al., (2016) found a significant reduction in IR in footballers who had experienced time loss from training due to hip and/or groin symptoms. Mosler et al., (2018) did not support this finding in a prospective cohort study, whereby only 1% of 113 injured participants were categorized as having hip-related groin pain, whereas 75% were adductor related. Comparison between these findings is therefore not possible.

Typically, hip joint ROM is assessed using low technology tools such as manual or digital goniometers which are economical and portable (Lea & Gerhardt, 1995). Although electromagnetic tracking systems have been proposed as reference standard, goniometers have greater ecological validity and have been shown to have good concurrent validity in the assessment of hip joint IR (Nussbaumer et al., 2010). They have also been shown to be reliable in the assessment of hip ROM in those with pathology such as OA (Holm et al., 2000) and FAIS (Nussbaumer et al., 2010). Recently, digital goniometers have increased in popularity, in part this may be down to its ease of use in the clinical setting when often only one practitioner is available (Lea & Gerhardt, 1995). Therefore, the aim of this study was to establish the intrarater and interrater reliability in the assessment of IR ROM using a digital goniometer.

4.1.1 Method

4.1.1.1 *Participants*

Eight healthy elite rowers (4 male, 4 female; 16 legs; age 26 ± 2 years; stature 183.9 ± 10.2 cm; body mass 82.6 ± 13.7 kg) volunteered for the study. Participants were recruited as part of the wider profiling study. Participant characteristics are presented in Table 4-1. Inclusion criteria for the study required participants to be injury free at the time of the study. Participants were excluded if they had any hip or knee pathology which would prevent them in anyway from completing the assessment. This included hip and/or knee surgery in the previous 12 months. Eligibility criteria and current injury status were established through face-to-face interviewing.

All participants gave written informed consent to participate in the study. The project was approved by the University of Salford Reasearch ethics committee (ref: HSR1819-049).

Table 4-1: Participant characteristics

	Males		**Females**	
	Mean ± SD	**95% CI**	**Mean ± SD**	**95% CI**
Age (years)	26 ± 2	23 – 28	27 ± 4	23 – 31
Body Mass (kg)	94.9 ± 2.9	91.6 – 98.2	70.3 ± 2.4	67.9 – 72.6
Stature (cm)	192.3 ± 0.6	191.7 – 193.0	172.9 ± 7.6	165.4 – 180.3

Standard deviation, SD; Confidence intervals, CI. N =8

4.1.1.2 *Procedure*

On arrival at the test location, stature and body mass measurements were collected as described in Section 3.1. The protocol for passive IR of the hip joint is described in section 3.2. In order to establish interrater reliability, each participant was assessed by two testers (E.J.A. & H.S.), who had a combined 26 years of experience working in musculoskeletal physiotherapy. Measurements were collected from both limbs. The testing order for rater and side, was randomised for each participant in order to limit systematic bias and raters were blinded to each others scores.

For intrarater reliability, the assessment was repeated 48 hours later by tester 1 (E.J.A.), at the same time point to negate the effects of diurnal variation. Participants were instructed not to change their daily routines and activity levels prior to each testing point. At the time of second assessment, the rater was blinded to the scores from the intital round of testing.

4.1.1.3 *Statistical Analysis*

Data was collected in degrees (°). Mean values across 3 tests were recorded for statistical analysis, along with standard deviations (SD) and 95% confidence intervals (CI).

To establish reliability of hip joint internal rotation, intraclass coefficient models were utilised: $ICC_{3,1}$ was used to ascertain intrarater reliability and $ICC_{2,k}$ was used for interrater reliability (Shrout & Fleiss, 1979). Standard error of measurement (SEM) and minimal detectable change (MDC) are also reported to reflect precision (Weir, 2005) and clinical signficiance (Haley & Fragala-Pinkham, 2006) of the data and to ensure any changes detected are not down to chance. The following formulas were utilised:

$$SEM = SD \times \sqrt{(1 - ICC)}$$

$$MDC = SEM \times 1.96 \times \sqrt{2}$$

ICC values were interpreted according to the following criteria suggested by Portney & Watkins (2000):

Poor reliability	< 0.5
Moderate reliability	0.5 – 0.75
Good reliability	0.75 – 0.9
Excellent reliability	>0.9

4.1.2 *Results*

Table 4-2 reports descriptive statistics for the data collected from testing. There was no pain reported by any participant during the assessment. Intrarater reliability for hip joint IR range of movement was good to excellent (ICC 0.88- 0.97) and interrater reliability was found to be excellent (ICC 0.91-0.99). Full results are reported in Table 4-3.

Table 4-2: Internal rotation descriptive data

	R1	**R2**	**R3**
Mean ± SD (°)	34.8 ± 8.4	34.1 ± 8.0	35.4 ± 9.7
95% CI	28.1 – 41.4	27.7 – 40.5	27.6 – 43.2

IR Internal rotation; Round 1, rater 1, R1; Round 2, rater 2, R2; Round 3, rater 1 R3; Standard deviation, SD, CI, confidence interval. N = 8

Table 4-3: Inter and Intrarater reliability of hip joint internal rotation

	Intrarater	**Interrater**
ICC **(95% CI)**	0.93 (0.78 – 0.98)	0.92 (0.73 - 0.98)
SEM	2.1°	2.5°
MDC	5.9°	7.0°

Intraclass coefficient, ICC; CI, confidence interval; Standard error of measurement, SEM; Minimal detectable change, MDC.

4.1.3 Discussion

The results of this study demonstrate that a simple assessment of hip joint internal rotation using a digital goniometer has good to excellent intra- and interrater reliability. These findings are superior to previous literature in healthy individuals for intrarater (ICC 0.77) (Prather et al., 2011) and interrater reliability (ICC 0.75-0.91) (Gradoz et al., 2018; Prather et al., 2011) using a manual goniometer, and is comparable to those with existing hip pathology (ICC 0.90-0.94)(Cibere et al., 2008; Holm et al., 2000). The low error measurements (Nussbaumer et al., 2010) and minimal detectable change values (Krause et al., 2015) reported are in line with previous research and demonstrate good clinical utility.

Fröjd and Bring (2016) previously investigated the validity of the EasyAngle© (EA) compared with a traditional plastic goniometer and found a high level of agreement (ICC 0.95) between the two devices. However, when comparing interrater reliability of the EA, limits of agreement were less favourable (26°, 0 0.85). As they did not report SEM or MDC, interpretation of clinical precision is difficult. Two other studies who have employed digital goniometers for hip ROM assessment in healthy individuals (Krause et al., 2015) and those with OA (Y.-H. B. Pua et al., 2008), both reporting good- excellent reliability with comparable error measurement (intrarater ICC 0.84-0.93; SEM 3.4°; MDC 7.8-8.6°). Although each of these investigated IR ROM in a seated position, in conjunction with the current study, these findings support the role of a digital goniometer in the longitudinal profiling of hip IR.

One study examined concurrent validity between a manual goniometer relative to an electromagnetic tracking system (ETS), reporting good validity between methods (ICC 0.88) and excellent levels of intrarater reliability using both assessments (ICC 0.95 and 0.90 respectively) (Nussbaumer et al., 2010). This study found that ROMs recorded using a goniometer were significantly greater than those recorded by the ETS ($P < 0.001$). It was hypothesised that traditional assessment using goniometers is likely to be a reflection of thigh on trunk angle as opposed to true hip joint ROM due to pelvic motion and anatomical location (Nussbaumer et al., 2010). This reinforces the need to adequately control the pelvis during assessment.

The high levels of reliability found in this study, may be in part explained by the levels of clinical experience of the testers used in this study. However, Gradoz et al., (2018) used students as examiners and found assessment of IR in the supine position had good to excellent reliability. They found this method to be superior to assessment in sitting which only demonstrated moderate reliability. The high levels of reliability reported when assessing in supine, irrespective of clinical experience, indicates that assessment in supine is preferable in the clinical environment. Gradoz et al., (2018) hypothesised these results may reflect an increased demand on the tester to move a limb against gravity when in sitting, alongside the increased trunk and pelvic stabilisation achieved when assessing in supine. It is likely that supine limits sagittal plane pelvic motion but not frontal or transverse. This study attempted to negate the impact of pelvic motion by stopping hip rotation at the point where pelvic motion was observed. Immobilising the pelvis using a seat belt attached to the plinth as described by Mosler et al., (2016), may have further improved the reliability of this method. This is critical as pelvic motion is known to have a direct impact on range of IR achieved with posterior pelvic rotation enabling greater ranges of IR to be achieved (Bagwell et al., 2016).

Much of the previous literature investigating IR ROM has assessed the hip joint in sitting whereas in this study IR was conducted in supine. This position has been shown to have better reliability than when assessed in sitting (Gradoz et al., 2018). A prone assessment was not considered as this position is not reflective of the bony congruency of the hip in relation in intra-articular hip pathology. Hip IR measured in flexion strongly correlates with the space between the femoral neck and acetabular rim (Wyss et al., 2007) and size of cam morphology (Kapron et al., 2012). Consequently, this methodology is in accordance with the diagnostic criteria recommended for FAIS and other forms of HRP.

The mean hip rotation reported in this study was 35° ± 9° with a low error measurement of 1-3°. This is in line with range of motion reported in other athletic populations such as football (32 ± 8°)(Mosler et al., 2017) and field hockey (33 ± 12°)(Beddows et al., 2020). Reliability studies involving participants with OA (23°; Holm et al.,2000) and FAI (26°; Nussbaumer et al., 2010) have demonstrated reduced values for IR. The findings of this study suggest that assessment of hip IR using this method can accurately measure range of motion.

4.1.4 Conclusion

The use of an EasyAngle© digital goniometer demonstrates a good level of precision and is reliable between testers and between repeated tests in the assessment of hip joint internal rotation. These findings support the use of this assessment method in future research for longitudinal tracking and profiling of the hip joint.

4.2 The intrarater reliability of 2-dimensional squat analysis

Squat based movement patterns are an essential component of many activities of daily living and sporting tasks (Myer et al., 2014; Schoenfeld, 2010), such as jumping and landing. They are also a fundamental element of many weight-room programmes aimed at enhancing athletic ability (Schoenfeld, 2010). A body-weight, DL squat is often used as a tool to screen lower limb biomechanics (Bell et al., 2013) as it enables functional and bilateral kinematic assessment at the hips, knees and ankles (Cook et al., 2014). Movement deficiencies detected during functional squatting tasks, may ultimately increase an athlete’s susceptibility to injury and/or limit their performance capabilities (Myer at al., 2014; Cook et al., 2014).

Squat depth, with and without symptom provocation can be a useful screening tool. Ayeni et al., (2014) found that when used as a diagnostic test for FAIS, pain provocation during maximal squat depth had moderate SN (75%; 95% CI 56.6-88.5%) and low SP with a 6.1% shift in pre- to post-test probability (Reiman et al., 2015). Several studies, (Bagwell, Snibbe, et al., 2016; Diamond et al., 2017; Lamontagne et al., 2009; Ng et al., 2015) have assessed squat mechanics in individuals with FAIS and found squat depth to be diminished when compared with controls. Only one study to date has considered FAIS compared with asymptomatic counterparts and controls (Ng et al., 2015). The study reported a reduction in squat depth in those with FAIS compared with those asymptomatic FAI, who in turn showed a reduction in squat depth compared with healthy controls. The study also found no difference in sagittal pelvic motion between those with asymptomatic FAI morphology and the control group highlighting that presence of morphology may not be the sole instigator of symptomatic movement dysfunction. Diamond et al., (2017) also reported that when individuals were forced to maintain an upright trunk position when squatting, those with FAIS demonstrated asymmetries in pelvic mechanics and hip kinematics. These findings highlight potential compensatory mechanisms, which may occur in those with dysfunctional hip motion. The analysis of squat mechanics may help in the early identification and management of those with underlying impingement morphology.

Three-dimensional (3D) motion analysis had been deemed the ‘gold standard’ for kinematic assessments (McLean et al., 2005), yet it is impractical in clinical practice and research involving large cohorts due to temporal and financial constraints. Two-dimensional (2D) video analysis, involving a standard video camera and a software package to conduct kinematic analysis (Norris & Olson, 2011), has been shown to correlate with 3D analysis in both the sagittal plane (Schurr et al., 2017) and frontal plane (McLean et al., 2005) as well as demonstrating strong criterion validity (Herrington & Munro, 2014). Consequently, 2D video analysis is frequently used to assess movement competencies (Schurr et al., 2017). To date, squat depth, and its associated kinematics, in relation to hip and groin dysfunction, have only been conducted using 3D assessment, therefore, the aim of this study was to establish the intrarater reliability in the 2D video analysis of a DL squat.

4.2.1 Method

4.2.1.1 *Participants*

Sixteen healthy, elite international rowers (8 males, 8 females) age 25 ± 2 years, stature 185 ± 10 cm, body mass 85.1 ± 12.7 kg, volunteered for the study. The participants were recruited as part of the wider profiling study. Participant characteristics are presented in Table 4-4. Inclusion criteria for the study required participants to be fully weight-bearing and injury free at the time of the study. Participants were excluded if they had any current injury or illness which may impair strength, motion or balance or inhibit them in anyway from completing the assessment. Eligibility criteria and current injury status were established through face-to-face interviewing.

All participants gave written informed consent to participate in the study. The project was approved by the University of Salford Reasearch ethics committee (ref: HSR1819-049).

Table 4-4: Participant characteristics.

	Males		**Females**	
	Mean ± SD	**95% CI**	**Mean ± SD**	**95% CI**
Age (years)	25 ± 2	24 – 26	26 ± 2	24 – 27
Body Mass (kg)	97.5 ± 6.8	93.0 – 102.0	75.2 ± 5.7	71.6 – 78.7
Stature (cm)	193 ± 8	188 – 198	178 ± 4	175 – 181

Standard deviation, SD; Confidence intervals, CI. N=16

4.2.1.2 *Procedure*

On arrival at the test location, stature and weight measurements were collected as described in Section 3.1.

Each participant performed nine body weight DL squats in total, while the test was captured by digital video footage. Both the squat procedure and camera set up protocol are described in Section 3.3. On completion of the assessment, the video footage was uploaded into Quintic (version 31; Quintic Consultancy Ltd, Coleshill, Birmingham, UK) for analysis.

A single examiner (E.J.A) watched and analysed each video, on a 12-inch computer screen. To establish intrarater reliability, the examiner analysed the videos on two separate occasions, one month apart. At the time of the second assessment the examiner was blinded to the original scores.

Two primary variables were considered: maximal squat depth in both the sagittal and frontal planes, and squat symmetry as measured by lateral drift and pelvic obliquity. Pelvic, knee and ankle kinematics were also analysed.

4.2.1.3 *Statistical Analysis*

The intrarater reliability of assessing DL squat kinematics using 2D video analysis was quantified using the intraclass coefficient ($ICC_{3,1}$) model (Shrout & Fleiss, 1979). Standard error of measurement (SEM) and minimal detectable change (MDC) were also reported to reflect precision (Weir, 2005) and clinical signficiance of the data (Haley & Fragala-Pinkham, 2006) to ensure any changes detected were not down to chance. The following formulas were utilised:

$$SEM = SD \times \sqrt{(1- ICC)}$$

$$MDC = SEM \text{ x } 1.96 \text{ x}\sqrt{2}$$

The mean of each of the block of three trials were used for statistical analysis.

4.2.1.4 *2D Data Processing*

For each trial, two still images were created in the repsective plane of movement. One in fully erect standing, and one at the lowest depth of the squat. The full process is described in Section 3.3.2.

4.2.2 Results

Intrarater reliability for DL squat kinematics measured using 2D video analysis were excellent (ICC 0.90- 1.00) apart from lateral drift and pelvic obliquity which were moderate and poor respectively (ICC 0.61 and 0.66). Full results are presented in Table 4-5 and Table 4-6.

Table 4-5: Intrarater reliability of 2D squat kinematics, frontal plane view

FRONTAL PLANE (POSTERIOR) View

	LATERAL DRIFT (mm)	% SQ DEPTH LEFT PSIS	% SQ DEPTH RIGHT PSIS	PELVIC OBLIQUITY (mm)
ICC	0.61	1.00	1.00	0.32
(95% CI)	(0.22 - 0.82)	(0.99 - 1.00)	(0.99 - 1.00)	(-0.54 - 0.41)
SEM	0.01	0.30	0.31	0.002
MDC	0.02	0.83	0.85	0.01

Intraclass coefficient (ICC) values with 95% confidence intervals (CI), standard error of measurement (SEM) and minimal detectable change (MDC). ST, standing; SQ. squat; GT, greater trochanter; PSIS, posterior superior iliac spine.

Table 4-6: Intrarater reliability of 2D squat kinematics, sagittal plane view

SAGITTAL PLANE (LATERAL) View								
	ST PELVIC ANGLE LEFT (°)	**ST PELVIC ANGLE RIGHT (°)**	**% SQ DEPTH LEFT GT**	**% SQ DEPTH RIGHT GT**	**KNEE ANGLE LEFT (°)**	**KNEE ANGLE RIGHT (°)**	**ANKLE ANGLE LEFT (°)**	**ANKLE ANGLE RIGHT (°)**
ICC	0.90	0.96	0.98	0.98	0.98	0.97	0.94	0.97
(95% CI)	(0.84 - 0.98)	(0.85 - 0.99)	(0.94 - 1.00)	(0.93 - 1.00)	(0.87 - 0.99)	(0.90 - 0.99)	(0.74 - 0.98)	(0.82 - 0.99)
SEM	0.98	0.92	0.75	0.84	1.42	1.99	0.82	0.60
MDC	2.72	2.55	2.08	2.31	3.92	5.49	2.28	1.65

Intraclass coefficient (ICC) values with 95% confidence intervals (CI), standard error of measurement (SEM) and minimal detectable change (MDC). ST, standing; SQ. squat; GT, greater trochanter.

4.2.3 Discussion

The findings of this study demonstrate that 2D video analysis of a body-weight DL squat has excellent intrarater reliability in the assessment of lower limb kinematics in both the frontal and sagittal planes, except for measures for pelvic motion which showed poor to moderate interrater reliability. To the authors knowledge, assessment of squat depth using this method has not previously been investigated.

This is the first study that has considered the 2D video analysis of squat depth in the frontal and sagittal planes. The SEM and MDC values reported were all less than 2.3%, which demonstrates good test reliability as it allows practitioners and researchers to confidentially interpret that any differences seen in frontal plane squat depth are not down to chance (Haley & Fragala-Pinkham, 2006). The squat depths reported, expressed as a percentage of leg length, were all markedly less than the the values reported during 3D motion analysis by 6-18% (Lamontagne et al., 2009; Ng et al., 2015). As well as using 3D analysis for data collection, these studies considered individuals with FAIS whereas the present study included healthy individuals, free from known pathology. This may contribute to the differences reported. Further work is required to understand the correlation between the two different methods of data collection for the metric of squat depth.

Several studies have considered the reliability and validity of 2D video analysis in frontal plane mechanics. These have primarily considered valgus motion around the knee, in a variety of functional tasks such as side step (McLean et al., 2005), single-leg squat (Gwynne & Curran, 2014; Harris-Hayes et al., 2014; Munro et al., 2012a), drop jump (Munro et al., 2012a), side jump (McLean et al., 2005) and single-leg landing (Munro et al., 2012a). These studies have reported good within day reliability (ICC 0.59-0.88) and good to excellent between day reliability (ICC 0.72-0.91) (Munro et al., 2012; Gwynne & Curran, 2014). Gwynne & Curran, (2014) reported equally favourable ICCs for between (0.74) and within-session (0.86) reliability when assessing the 2D video analysis of a single-leg squat. Further studies (McLean et al., 2005; Gwynne & Curran, 2014) have also reported a strong correlation between their findings with 2D video analysis compared with 3D motion analysis in the consideration of FPPA.

Each of the squat parameters considered in the sagittal plane had excellent intrarater reliability (ICC 0.90-0.98) with good SEM and MDC. These finding support those previously reported by Norris & Olson, (2011) and Gribble, Hertel, Denegar & Buckley, (2005) during mechanical lifting tasks (ICC 0.98-0.99) and the SEBT (ICC 0.81-0.89). The error measurements reported in the present study were comparable for ankle range of movement (1.65 - 2.28° degrees) but worse for knee range of movement (3.92 – 5.49 degrees) than those values previously reported (Gribble et al., 2005; Norris & Olson, 2011). However, the mean knee ranges achieved when squatting in this study were 4.3° greater than the largest knee flexion ranges reported by Norris & Olsen (2011). Norris & Olson, (2011) also found there was no significant difference between hip or knee angles obtained via 2D video analysis software compared with those measured using a standard goniometer from the same video recording.

The measures relating to the pelvis were deemed to have poor to moderate intrarater reliability. One study in runners demonstrated excellent intrarater reliability for pelvic obliquity (ICC 0.96), but found a lack of correlation between 2D video analysis of pelvic obliquity relative to 3D motion analysis (Maykut et al., 2015). As pelvic motion is a derivative of femoral-acetabular (Ross et al., 2014) and lumbopelvic motion (Vleeming & Willard, 2010), any functional impairments in pelvic motion may be a consequence of aberrant spinal or hip kinematics secondary to regional interdependence (Sueki et al., 2013). Two-dimensional capture of frontal plane movements may not accurately reflect 3D kinematics as it is difficult to measure sagittal plane and rotational movements (Ageberg et al., 2010; Willson et al., 2006), therefore composite movements around the pelvis will not be accurately determined. This is compounded by the fact that spinal kinematics were not considered in this study. These limitations may explain why the two frontal plane pelvic measures demonstrated poor reliability.

Previous literature has considered the role of a deep squat in injury prediction as part of a wider movement screen, known as the Functional Movement Screen^{TM} (FMS^{TM}) with mixed results. Dorrel et al., (2018) reported that the squat component of the FMS^{TM} was inaccurate in predicting the severity of musculoskeletal injuries, however Franklin et al., (2018) found that knee joint range of motion corresponded with the absence of back pain. The FMS^{TM} is a subjective, point scoring assessment system, which has been shown to have substantial to excellent agreement between raters (Minick et al., 2010; Onate 2012). Depth of squat is a component of the scoring system, but the subjective rating does not quantify squat depth sufficiently to help understand the kinematics associated with the development of hip pathology. In addition, the FMS^{TM} deep squat instructions specifies placing the arms above the head, which has been shown to markedly affect squatting potential due to the additional stability and mobility requirements placed on the wider kinetic chain (McMillian et al., 2016). This limits transferability of the FMS^{TM} deep squat test, and its findings, to the methodology employed in this thesis.

A limitation of the present study was the use of tape as surface markers for kinematic analysis. Motion of the skin relative to the underlying bone during activity, is a phenomenon known as soft tissue artefact (STA). During gait analysis, kinematics achieved via skin markers have been shown to be reliable, although not representative of the movement of the underlying bone (Benoit et al., 2006). It is recognised that the assessment of joint kinematics using skin markers comes with an associated error measurement (Camomilla et al., 2017) and therefore findings should be interpreted with caution. The accuracy and validity of STA is a known challenge in the field of biomechanics and outside of the scope of this thesis. The utilisation of either fluoroscopy or the insertion of pins into bones as a potentially more specific assessment of motion analysis (Camomilla et al., 2017) was not financially or ethically viable in this specialised population, whereas light reflective markers may have been a more suitable alternative. The latter may have also enabled assessment of pelvic tilt, which was not possible in this study as the ASIS tape marker was not visible during the squats deepest position. Furthermore, the use of two cameras to achieve motion capture may also have improved the reliability of the test. Using only one camera meant sagittal and frontal films were obtained from different squats which may have introduced within subject variability.

Another potential limitation of this study is the risk of perspective, or parallax error, associated with 2D video analysis. The methodological approach used should minimise the risk of error, however, any movements that occurs outside of the intended plane of motion e.g., transverse plane pelvic rotation when filming a sagittal view, may distort the accuracy of the measurements.

Participants were asked to stand hip distance apart, but no instruction was given with regards to foot position. Foot distance and foot angle have both been shown to influence accuracy of both loaded squat (Escamilla et al., 2001) and dead lift (Escamilla et al., 2000) when comparing 2D to 3D motion analysis. A narrow stance with small foot angles has been shown to produce satisfactory results during 2D video analysis in comparison to 3D analysis. However, significant measurement errors occur as these angles increase, with wide stances producing error measurements up to twice the size, compared with narrow based squats (Escamilla et al., 2001). This is a consequence of movements occurring out of the sagittal plane.

According to Donohue et al., (2015),when assessing frontal plane hip kinetics and kinematics, a DL squat has poor correlations with single-leg squatting and landing tasks. Therefore, the DL squat may not be sensitive enough to detect movement dysfunction in athletic populations and sports which require high levels of force absorption. However, in relation to depth of squat, which has specific relevance in the topic of hip impingement, the excellent reliability found in the present study warrants the utilisation of the DL squat as part of a wider screening proforma.

4.2.4 Conclusion

Squatting is a movement pattern which is fundamental to both sporting performance and athlete health (Myer at al., 2014; Cook et al., 2014). The present study demonstrates excellent intrarater reliability in the 2D video analysis assessment of squat depth, knee, and ankle kinematics during a double-leg squat task. The proposed methodology supports its utilisation as part of a screening assessment of the lower limb.

Further work is needed to improve the accuracy, reliability, and assessment in the 2D assessment of the pelvis in both the sagittal and frontal planes. Due to the poor reliability found, this metric will not be taken forwards in this thesis.

4.3 Y-balance assessment reliability

The star excursion balance test (SEBT) is a dynamic postural control assessment, which is used to identify dynamic balance deficits (P. Gribble et al., 2012) by challenging the proprioception, strength and flexibility (Coughlan et al., 2012). The SEBT has been recognised as a valid and reliable assessment in the prediction of lower limb injury (Plisky et al., 2009) and has been used to identify balance deficits in those with chronic ankle instability (Hertel, Braham, Hale & Olmsted-Kramer, 2006) and anterior cruciate ligament deficient knees (Herrington, Hatcher, Hatcher & McNicholas, 2009). It has also been shown to successfully distinguish between individuals with FAIS and healthy controls (Johansson & Karlsson, 2016). Both the posterolateral (PL) and posteromedial (PM) reach directions have been shown to have strong correlations with pain and symptoms in those with FAIS as well as demonstrating a significant reduction in range achieved in the PL direction between the symptomatic and asymptomatic limbs (Johansson & Karlsson, 2016).

The original SEBT involves standing on one leg in the centre of a star-shaped grid, and performing a series of single-legged squats while the non-weight bearing leg reaches as far as possible along the respective ‘arms’ of the star (see Figure 4-1). The aim is to achieve a maximal reach distance with the non-weight bearing limb while maintaining balance on the weight bearing side.

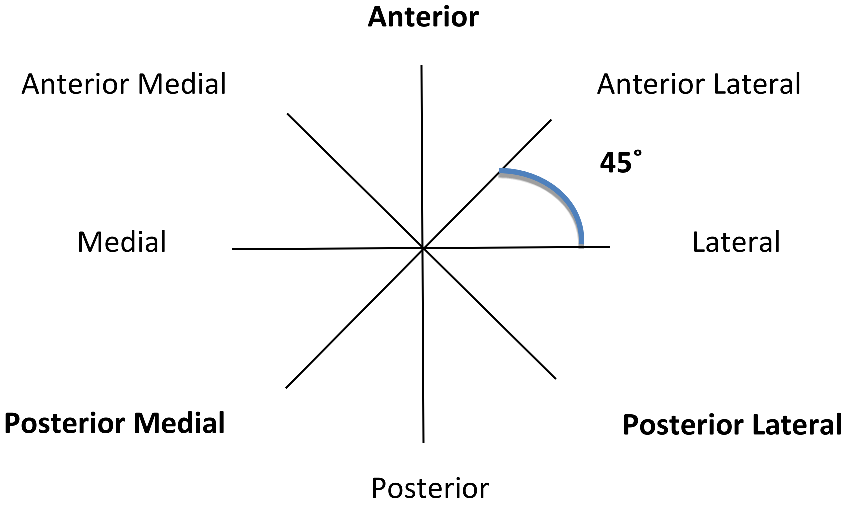


Figure 4-1: SEBT assessment directions relative to weight bearing on the left leg. Directions in ***bold*** *indicate those directions incorporated into the Y-balance test.*

More recently, the Y-balance test has been developed to improve time efficiency (Shaffer, 2013) and repeatability (Plisky et al., 2009) of dynamic balance assessment, adopting only 3 of the original SEBT directions (anterior, posterior medial, posterior lateral (see Figure 4-1(Shaffer, 2013). Although the Y-balance assessment can be conducted using taped floor markings as per SEBT, a commercially available instrumented version has been developed, the Y-balance Test Kit^{TM} (Move2Perform, Evansville, Indiana, USA). The kit consists of three pieces of PVC pipe, a stance platform elevated 1 inch off the floor, and a rectangular reach indicator block (see Figure 3-7).

The primary aim of this study was to establish the test-retest reliability of the Y-balance test using both the modified SEBT (mSEBT) with tape, and the newer instrumented version. The second aim of the study was to compare the scores from the two different methods of Y-balance data collection to determine which assessment would be used during the primary study phase.

4.3.1 Method

4.3.1.1 *Participants*

A convenience sample of eight elite rowers (4 males and 4 females), age 27.3 ± 3.0 years, stature 178.2 ± 6.0 cms, body mass 82.2 ± 9.4 kgs, volunteered for the study. Seven of the eight participants were right foot dominant. Participant characteristics are presented in Table 4-7. Inclusion criteria for the study required participants to be between the ages of 18 and 35 years of age, with no history of lower limb injury for the preceeding 3 months. Individuals were excluded if there were suffering with any current injury or illness which may impair strength, motion or balance or inhibit them in anyway from completing the assessment.

All participants gave written informed consent to participate in the study. The project was approved by the University of Salford Reasearch ethics committee (ref: HSR1819-049).

Table 4-7: Participant characteristics

	Mean ± SD	**95% CI**
Age (years)	27.3 ± 3.0	25.2 – 29.3
Body Mass (kg)	82.2 ± 9.4	75.7 – 88.7
Stature (cm)	178.2 ± 6.0	174.0 – 182.3
Leg Length (cm)	96.0 ± 5.0	92.6 – 100.1

Standard deviation, SD; Confidence intervals, CI. N =8

4.3.1.2 *Procedure*

On arrival at the test location, stature, body mass and leg length measurements were collected as described in section 3.1. Participants participated in 2 test sessions on the same day, separated by more than 4 hours. Each test session involved the participant conducting 2 versions of the Y- balance assessment:

1. Using a commerically available device, Y-balance Test Kit^{TM}. (Move2Perform, Evansville, IN).
2. mSEBT, using zinc oxide tape affixed to the floor of the assessment area as described by Coughlan et al., (2012).

The protocol for completion of the Y-balance, including warm up, is previously described (See section 3.4). Individuals were randomly assigned as to which test method they conducted first. After a break of 5 minutes, the second test method was then performed. The same protocol, and test order, was then repeated on the same day, separated by more than 4 hours in order to minimise the affect of fatigue. Each assessment was conducted by the same rater (E.J.A).

4.3.1.3 *Statistical Analysis*

In order to allow comparison of data between participants, reach distance was normalised for leg length and expressed as a percentage (%LL) using the following formula:

$$(\text{Excursion distance} / \text{leg length}) * 100$$

Mean and maximum reach differences across 3 tests were calculated along with standard deviations (SD) and 95% confidence intervals (CI) for each of the 3 reach directions; Anterior (ANT), Posterolateral (PL) and Posteromedial (PM). Mean and maximum composite scores were also reported as the sum of each of the 3 reach directions.

4.3.1.3.1 Test-retest reliability

In order to ascertain test-retest reliability of the Y-balance assessment, data was analysed using the intraclass coefficient ($ICC_{3,1}$) model (Shrout & Fleiss, 1979). Standard error of measurement (SEM) and minimal detectable change (MDC) are also reported to reflect precision (Weir, 2005) and clinical signficiance (Haley & Fragala-Pinkham, 2006) of the data and to ensure any changes detected are not down to chance. The following formulas were utilised:

$$SEM = SD \times \sqrt{(1 - ICC)}$$

$$MDC = SEM \times 1.96 \times \sqrt{2}$$

ICC values were interpreted according to the following criteria suggested by Portney & Watkins (2000):

Poor reliability	< 0.5
Moderate reliability	0.5 – 0.75
Good reliability	0.75 – 0.9
Excellent reliability	>0.9

4.3.1.3.2 *Method comparison*

To compare reach distances achieved between the two different data collection methods, paired-sample *t* tests were conducted, with a pre-identified α level of $p \leq 0.05$. Pearson correlation coeficients (*r*) were used to determine the relationship and variance between the two groups of data.

4.3.2 Results

Table 4-8 and Table 4-9 report descriptive statistics for the data collected from testing.

4.3.2.1.1 *Test-retest reliability*

Test-retest reliabilty for the mean reach distances had good to excellent ICC values using both YBT Kit^{TM} (YBT) and the mSEBT, ranging from 0.82 to 0.91, with the exception of the anterior reach using the mSEBT method which showed only moderate reliability (0.62). SEM and MDC values for isolated reach directions ranged from 1.27 to 3.43 %LL, and 3.51 to 9.47 %LL repsectively (see Table 4-8 and Table 4-9).

Table 4-8: Intrarater Reliability of YBT.

Direction	**YBT, Normalised Reach (%LL) Mean ± SD (95% CI): TEST 1**	**YBT, Normalised Reach (%LL) Mean ± SD (95% CI): TEST 2**	**ICC (3,1) (95% CI):**	**SEM (%)**	**MDC (%)**
Anterior	68.10 ± 4.52 (66.19, 70.62)	69.27 ± 3.51 (66.55, 69.98)	0.91 (0.76 – 0.97)	1.27	3.51
Posterolateral	117.54 ± 9.16 (113.05 – 122.02)	117.05 ± 8.04 (113.11 – 121.00)	0.89 (0.70 – 0.96)	2.83	7.82
Posteromedial	109.10 ± 10.84 (103.79, 114.41)	108.53 ± 8.61 (104.31, 112.75)	0.88 (0.66 – 0.95)	3.42	9.47
Composite	295.03 ± 20.57 (284.96, 305.11)	293.85 ± 17.30 (285.37, 302.32)	0.88 (0.67 – 0.95)	6.57	18.16

YBT, Y-balance Test Kit™. Normalised reach (%LL) = (reach distance/leg length) x100; SD, standard deviation; CI, confidence interval; Intraclass coefficient (ICC) values, standard error of measurement (SEM) and minimal detectable change (MDC) across all limbs.

Table 4-9: Intrarater Reliability of mSEBT.

Direction	**mSEBT, Normalised Reach (%LL) Mean ± SD (95% CI): TEST 1**	**mSEBT, Normalised Reach (%LL) Mean ± SD (95% CI): TEST 2**	**ICC (3,1)**	**SEM (%)**	**MDC (%)**
Anterior	72.63 ± 5.04 (70.16, 75.09)	72.43 ± 5.14 (69.91, 74.95)	0.62	3.06	8.46
Posterolateral	113.59 ± 6.86 (110.23, 116.95)	115.02 ± 5.42 (112.37, 117.67)	0.89	2.19	6.07
Posteromedial	108.77 ± 9.04 (104.34, 113.20)	110.0 ± 7.31 (106.50, 113.66)	0.87	3.02	8.36
Composite	297.77 ± 14.12 (290.85, 304.69)	297.53 ± 14.76 (290.30, 304.76)	0.82	6.15	17.01

mSEBT, modified star excursion balance test. Normalised reach (%LL) = (reach distance/leg length) x100; SD, standard deviation; CI, confidence interval; Intraclass coefficient (ICC) values, standard error of measurement (SEM) and minimal detectable change (MDC) across all limbs.

4.3.2.2 *Method Comparison*

No significant differences were observed in the reach distances achieved in the PM directions when comparing the 2 different methods of data collection, or when looking at composite scores (*p* >0.05). Participants, however, reached significantly further in anterior direction with the mSEBT method compared with the Y-balance Test Kit^{TM}, on average achieving 5.9% further (*p* < 0.01) but had shorter reach distances in the PL direction (-2.7%, p < 0.01).

A strong, positive relationship was found between the two test methods when considering the posterior directions (*r* = 0.81-86) but only a medium correlation was found in the anterior direction with the YBT accounting for only 67% reach distance achieved on the mSEBT.

Table 4-10 Comparative data for YBT verses mSEBT methods of data collection.

	Mean Ant	**Mean PL**	**Mean PM**	**Mean Composite**
***P*-value**	0.0^{ψ}	0.0^{ψ}	0.68	0.41
r	0.67	$0.86^{\psi\psi}$	$0.81^{\psi\psi}$	$0.83^{\psi\psi}$

r = Pearson correlation coefficients. $^{\psi}$ = significant difference, P <0.05, $^{\psi\psi}$ = strong correlation

4.3.3 Discussion

4.3.3.1.1 Test-retest reliability

The results of this study indicate that the assessment of dynamic postural control using the Y-balance test has good to excellent test-retest reliability using the YBT Kit^{TM} and moderate to excellent using the mSEBT. This reflects the findings of several other studies looking at the reliability of the mSEBT (Hertel et al., 2000; Hyong & Kim, 2014; Munro & Herrington, 2010) and the YBT (Plisky et al., 2009). The normalised SEM measurement demonstrated that true reach scores lie within 1.27 – 3.42% and 2.19 – 3.06% for the YBT and mSEBT respectively which align with those previously reported when using the SEBT (Munro & Herrington, 2010). Although both tests show acceptable reliability, the YBT Kit^{TM} was shown to be superior in the anterior direction. The use of a reach indicator block also allows the examiner to focus on the technical execution of the task and not simply the reach position (Fullam et al., 2014). In combination, these factors lead to the conclusion that the YBT Kit^{TM} is the preferable choice for the experimental chapter.

Munro & Herrington (2010) reported that the SEBT measures would need to increase by more than 6.8% between tests to be classed as a true change in performance whereas the MDC reported in this study ranged from 3.51-9.47% depending on method used and direction tested. Our study used a smaller sample size which may explain the difference in findings. Understanding the true MDC has important implications in the interpretation of research findings in order to establish when a change is beyond measurement error (de Vet & Terwee, 2010). Johansson & Karlsson (2016) found a 9% and 12% difference in maximal excursion distances in the PM and PL direction between those with FAIS compared with those without. Based on the MDC values reported, this can therefore be interpreted as a true change. Olmsted, Carcia, Hertel & Shultz, (2002) also reported a significant difference in reach distance between those with and without chronic ankle instability. The values they reported were not in line with the MDC reported by Munro & Herrington (2010) but may have been acceptable based on some of our findings.

Test-retest reliability of composite reach showed excellent reliability and low error measurement, however, the MDC ranged between 17.01-18.16%. Bulow et al., (2019) identified the potential bias created by assessing the reach distances in this manner. In this study, composite scores were equal between test groups, but the contribution of reach distance varied.

4.3.3.2 *Method Comparison*

The study showed that Y-balance assessment using the taped mSEBT method is comparable to using YBT when considering the PM direction, but not in the anterior or PL directions. There was a significant difference in the anterior and PL reach distances, with greater anterior distances achieved using the YBT method but greater PL reach distances using the mSEBT method. These findings conflict with previous studies which have demonstrated superior anterior reach distances using the mSEBT compared with the YBT and no differences in posterior reach directions (Coughlan et al., 2012; Fullam et al., 2014). Average reach distances in these studies were lower in the anterior (59-60%) and PL (102-106%) directions which may have influenced the outcome.

It has been suggested that the differences seen in reach distances between the two methods may arise because of the differing control mechanisms employed with each of the techniques (Coughlan et al., 2012). In the YBT method, the reach foot remains in contact with the reach indicator block, giving the participant constant proprioceptive feedback whereas the lack of afferent feedback in the mSEBT elicits a feedforward mechanism whereby the individual will only receive feedback once contact with the tape has been made (Coughlan et al., 2012). However, as there were no discernible differences seen in the PM reach direction, these balance mechanisms cannot wholly be responsible for the differences seen in the other directions.

Alongside the somatosensory system, the visual system is known to contribute to postural control (Peterka, 2002). As vision is not impaired when reaching anteriorly, but is impaired posteriorly, the visual system contribution to postural control also doesn't explain the differences seen in testing. It is likely therefore that the differences seen in anterior reach distances, and the variance in reliability when reaching forwards, are due to mechanical causes which were not assessed on this study. Fullam et al., (2014) reported that reduced anterior reach distances corresponded with a difference in kinematic profiles at the hip joint. When using the YBT method, the individual is elevated on the standing block and therefore required to reach below the height of their standing surface to achieve contact with the indicator block. This potentially requires the participant to squat lower and may reflect the increased hip flexion reported using this methodology and corresponding reduction in excursion distances. Both hip and knee flexion ranges have previously been identified as predictors of reach distances during the SEBT (Robinson & Gribble, 2008).

During the YBT, the potential for trunk motion to contribute to maintenance of centre of mass is greater when reaching posteriorly relative to anteriorly which may partly justify why differences are seen in some but not all 3 directions. Chimera, Smith & Warren (2015) found that individuals with trunk and/or back injuries demonstrated greater variability in all reach distances which may verify the role the trunk plays in achieving dynamic postural control.

One further study has investigated the differences between the YBT and mSEBT (Bulow et al., 2019), however they found a difference in all 3 reach directions when comparing methodology with the mSEBT demonstrating superior reach distances. However their demographic was adolescent females which make explain the differences seen in this study as both females (Weeks, Carty, & Horan, 2015; Willson, Ireland, & Davis, 2006) and decreasing age (Agresta et al., 2017) are known to negatively affect single-leg squat performance.

A potential limitation of this study is the protocol used. Repeated testing was conducted on the same day therefore diurnal variation and fatigue may have played a role. Other studies (Coughlan et al., 2012; Fullam et al., 2014) conducted their trials a week apart whereas Plisky et al., (2006) waited only twenty minutes, yet all drew similar conclusions. The present study familiarised the participant to the assessment on the day of data collection. Participants were instructed to complete 4 practice trials as maximum excursion distances have been shown to stabilise following this number of trials (Robinson & Gribble, 2008; Munro & Herrington, 2010). An additional familiarisation session prior to the testing day may have strengthened the work in this study by aiding a bigger learning period as is recommended by Kinzey & Armstrong (1998).

4.3.4 Conclusion

The Y-balance test shows good to excellent absolute reliability and acceptable error measurements regardless of the methodology used, which supports the use of either approach in clinical practice or research. The YBT method was however shown to have superior test-retest reliability in the anterior reach direction.

Practitioners should be cautious not to use findings from the YBT interchangeably with the mSEBT, especially when looking at anterior reach distances due to the poor correlation found between the two assessment methods. Due to the findings in this study, the YBT will be taken forwards as the preferred protocol in the study chapters.

4.4 The intrarater reliability of a qualitative scoring system in the assessment of a single-leg squat

The single-leg squat (SL squat) is commonly used as a lower extremity screening tool (Lewis et al., 2015; McGovern et al., 2018; Weeks et al., 2012) as it is representative of the physical demands and dynamic control requirements of many sporting tasks (McGovern et al., 2018). It has been identified as an appropriate alternative to landing tasks in replicating frontal plane loading and kinematics (Donohue et al., 2015) Three-dimensional (3D) motion analysis is considered to be ‘gold standard’ in the assessment of lower limb biomechanics (McLean et al., 2005), yet it is impractical in clinical practice and research involving large cohorts. In comparision, visual assessment of a SL squat, is deemed to be reliable and easy to administer in the clinical setting (Ressman et al., 2019; Whatman et al., 2013).

A SL squat has been suggested as a dynamic functional assessment of the stability of the hip and pelvis (Grimaldi, 2011). Literature to advocate the SL squat use in the diagnosis of hip and groin pain is currently lacking, although it has been shown to be valid in the assessment of hip joint kinematics and muscle function (Kivlan & Martin, 2012; McGovern et al., 2018). Muscle strength (Carsartelli, et al., 2011), hip kinematics (Lewis et al., 2018) and movement control (Botha et al., 2014) have all been shown to be impaired in those with FAIS, during similar tasks such as stepping down (Lewis, Loverro, et al., 2018) and when performing a SL squat in academy footballers (Botha et al., 2014).

Muscular weakness at the hip is a key feature of FAIS (Casartelli et al., 2011; Kierkegaard et al., 2017). Hip abduction torque is reduced in those who perform poorly on SL squat tasks (Crossley et al., 2011) and greater strength has been shown to decrease frontal plane projection angle (FPPA) and dynamic valgus motion at the knee (Claiborne et al., 2006; Horan et al., 2014). As dynamic valgus of the knee leads the hip into a position of impingement, a SL squat task would appear valuable in better understanding predisposing factors of HRP including FAIS.

A single leg loading qualitative assessment tool (QASLS), as described by Herrington, Myer & Horsley (2013), has been developed as a means to quantify lower limb alignment based on the criteria of Crossley et al., (2011) and Whatman et al., (2013). It is a dichotomous scoring system which allows for rating of movement deviations occurring at individual body parts. Utilisation of the QASLS scoring system when rating a SL squat task has been reported as an effective and reliable tool in profiling for injury risk (Horobin & Thawley, 2015) and it has been shown to have excellent intra and interrater reliability (Dawson & Herrington, 2015). Furthermore, it has been found to have strong criterion validity when compared with 3D motion analysis (PEA 98.4%; kappa 0.97) (Herrington & Munro, 2014).

The aim of this study was to determine the intrarater reliability of the QASLS in the assessment of a SL squat task in preparation for its application as a screening tool in the identification of risk factors for HRP in elite athletes. It was hypothesised that the test would have good intrarater agreement.

4.4.1 Method

4.4.1.1 *Participants*

A convenience sample of eight elite rowers (4 male, 4 female; 16 legs), who had already volunteered for the profiling study were selected at random. Participants were age 26 ± 2 years, stature 184 ± 7 cm, body mass 84.2 ± 12.2 kg and completed an average of 30 hours training per week. Participant characteristics are presented in Table 4-11. Inclusion criteria for the study required participants to be fully weight-bearing and injury free at the time of the study and for the previous 6 months. Participants were excluded if they had any current injury or illness which may impair strength, motion or balance or inhibit them in anyway from completing the assessment.

All participants gave written informed consent to take part in the study which was approved by the University of Salford Reasearch ethics committee (ref: HSR1819-049).

Table 4-11: Participant characteristics.

	Males		**Females**	
Characteristic	**Mean ± SD**	**95% CI**	**Mean ± SD**	**95% CI**
Age (years)	27 ± 1	26 – 28	25 ± 2	24 – 27
Body Mass (kg)	92.6 ± 11.8	81.0 - 104.1	75.8 ± 3.9	71.9 – 79.6
Stature (cm)	189 ± 6	183 – 195	180 ± 3	177 – 183
Leg Length (cm)	100 ± 5	95 – 104	96 ± 1	95 – 97

Standard deviation, SD; Confidence intervals, CI. N = 8

4.4.1.2 *Procedure*

On arrival at the test location, stature, weight and leg length measurements were collected as described in section 3.1. Eligibility criteria and current injury status was established through face-to-face interviewing.

Each participant performed three single-leg squats, on each leg, while the test was captured in the frontal plane by digital video footage. Both the procedure and camera set up protocol are described in section 3.5. On completion of the assessment, the video footage was uploaded into Quintic (version 31; Quintic Consultancy Ltd, Coleshill, Birmingham, UK) for analysis.

A single examiner (E.J.A) watched and rated each video three times, in real-time speed, on a 12-inch computer screen, using the standardised QASLS rating sheet (see Figure 3-9). The dominant strategy for each of the body part regions, during the three SL squat was recorded. Scoring was defined as a zero for an appropriate strategy and one for an inappropriate movement in each region. Best overall score being 0 and worst possible overall score being 10 points. (Herrington, Myer, & Horsley, 2013).

To establish intrarater reliability, the examiner repeated the video assessment one month later. At the time of the second assessment the examiner was blinded to the original scores.

4.4.2 Statistical Analysis

Test agreement and reliability of the QASLS were quantified. Percentage exact agreement (PEA) and kappa coefficients (κ) were employed for the individual components of the test, and intraclass coefficient ($ICC^{3,1}$) was used to establish intrarater reliability. Both legs were examined leading to 16 data points in total.

The following formula was used to establish PEA:

$$PEA = (agreed/agreed + disagreed) \times 100$$

4.4.3 *Results*

The QASLS was found to have excellent intrarater reliability (ICC^{3,1} 0.94) with a low SEM (0.45) and MDC (1.26) (See Table 4-12).

The percentage of exact agreement and kappa coefficients for the individual components are reported fully in Table 4-13. *Post-hoc* analysis showed that leg dominance played no role in the accuracy or reliability measures.

Table 4-12 Intrarater reliability of QASLS assessment.

Mean QASLS Score R1 (±SD)	**Mean QASLS Score R2 (±SD)**	**ICC^{3,1} (95% CI)**	**SEM**	**MDC**
3.9 (1.9)	3.8 (1.9)	0.94 (0.82 - 0.98)	0.45	1.26

Round 1, R1; Round 2, R2; Standard deviation, SD. N = 30. Intraclass coefficient (ICC) values, 95% confidence intervals (CI), standard error of measurement (SEM); minimal detectable change (MDC).

Table 4-13: Percentage exact agreement (PEA) & kappa coefficient for individual QASLS components.

		PEA (%)	Κ
Arm strategy		100	1.00
Trunk alignment		100	1.00
Pelvic plane	Loss of horizontal plane	56	0.15
	Excessive tilt or rotation	81	0.60
Thigh motion	WB thigh moves into hip adduction	100	1.00
	NWB thigh not held in neutral	100	1.00
Knee position	Noticeable valgus	100	1.00
	Signficant valgus	100	1.00
Steady stance	Touches down with NWB foot	100	1.00
	Stance leg wobbles noticeably	88	0.67

WB; weight bearing, NWB; non-weight bearing.

4.4.4 Discussion

Identification of biomechanical deficiencies during functional movement patterns are an important component of effective rehabilitation and in the identification of injury risk. The aim of this study was to establish the intrarater reliability of the QASLS in the assessment of a SL squat. In accordance with the parameters set by Portney & Watkins (2000) the results of this study demonstrated the QASLS to have excellent intrarater reliability. The present study concurs with Almangoush Al(2015) and Dawson & Herrington (2015) who also reported excellent reliability for the use of QASLS.

Previously, the reliability of visual assessment of a SL squat using a subjective score has been shown to be inconclusive (Barker-Davies et al., 2018; Chmielewski et al., 2007; Crossley et al., 2011; Poulsen & James, 2011; Weeks et al., 2012; Whatman, Hing, et al., 2012; Whatman et al., 2013). The lack of homogeneity in prior work potentially explains this. The level of detail used in the subjective scoring criteria varies between studies, as does the numerical scoring system used, and therefore each study elicits differing intrarater reliability.

Weeks et al., (2012) employed a 10-point scale to rate the overall performance of a SL squat. Intrarater reliability was reported to be excellent for physiotherapists (ICC = 0.81) but only moderate for students (ICC = 0.71). In comparison, Poulsen & James (2011), who adopted a 4-point ordinal assessment, reported an intrarater reliability ranging from 0.38 to 0.94. Chmielewski et al., (2007) utilised an overall, full-body assessment method and found higher percentage agreement between and within-rater compared with an alternative method which took into consideration of trunk, pelvis, and hip motion. Conversely, Whatman et al., (2012) found no difference in intrarater agreement between methods using less than a 3, or more than a 4-point scoring system. Both Crossley et al., (2011) and Whatman et al., (2013) reported substantial intrarater reliability using three and six-point scoring systems, reporting 73-86% and 79-88% PEA, respectively. The QASLS method of assessment offers more explicit criteria for the assessment of each body segment compared to the guidelines suggested by other authors (Chmielewski et al., 2007; Crossley et al., 2011; Whatman et al., 2013), which may account for the higher intrarater reliability reported. Interrater reliability of the QASLS system has also been shown to be good (Horobin & Thawley, 2015) to excellent (Almangoush, 2015), which is superior to other, less explicit, visual grading methods (Chmielewski et al., 2007; Crossley et al., 2011; Poulsen & James, 2011; Weeks et al., 2012; Whatman, Hing, et al., 2012; Whatman et al., 2013).

The QASLS scoring method rates movement quality of individual body segments. When considering reliability for each body segment, 7 elements reported agreement of 90% and above with strong to perfect kappa coefficients (κ = 0.88 - 1.00). All bar those determinants of pelvic performance reported greater than 85%. Although lower than the other body regions, scoring of pelvic mechanics in the sagittal and transverse planes was still deemed to be substantial (81%) although not in the frontal plane (56%). Both pelvic elements showed weak levels of agreement (κ = 0.15 - 0.60). Whatman et al., (2012), who reported PEA of between 50-96% dependent on level of clinical experience, however, their method involved grouping frontal and transverse pelvic motion. Similarly, Barker-Davies et al., (2018) found that assessment of both pelvic tilt and obliquity were less reliable compared to either hip adduction or trunk flexion assessment. Herrington & Munro (2014) found the only differences between qualitative scoring and 3D motion analysis related to scoring of pelvic rotation. In the present study analysis was performed using two-dimensional (2D) video in the frontal plane. This method is difficult to accurately establish motion in either the transverse or sagittal planes, which may explain the reduction in reliability reported at the pelvis. The addition of a secondary camera recording motion in the sagittal plane may have helped to improve accuracy.

It has been documented that FPPA are reliably assessed by visual observations (Barker-Davies et al., 2018; Stensrud et al., 2011; Ugalde et al., 2013), by both novice and experienced practitioners (Harris-Hayes et al., 2014; Weeks et al., 2012), with good to excellent correlation with 2D video analysis (Ageberg et al., 2010; Harris-Hayes et al., 2014; Stensrud et al., 2011). The findings of the present study supported this, with PEA for noticeable and marked valgus knee position reported at 100%. This was greater than the PEA reported by Whatman et al, (2013) for a single-leg small knee bend (PEA = 83%). Two studies found that those subjectively rated as having an increased FPPA, had increased hip internal rotation (Ageberg et al., 2010; Whatman et al., 2013) and adduction (Whatman et al., (2013) during 3D motion analysis. Barker-Davies et al., (2018) also found a relationship between clinicians' composite scores of SL squat and hip internal rotation moment, however they also reported poor validity against 3D kinematic data.

DiMattia et al., (2005) reported high specificity but low sensitivity in the visual assessment of greater than 10° hip adduction during a SL squat. Interrater reliability in this case was low to fair, with two-thirds of agreement occurring due to subjects not demonstrating excessive knee valgus. The study also reported a poor correlation between hip abductor muscle strength and dynamic knee valgus during a SL squat, although several more recent studies have refuted these findings (Claiborne et al., 2006; Crossley et al., 2011; Horan et al., 2014). Functional tests such as a SL squat may therefore add value in the initial screening of lower limb muscle function.

The QASLS criteria demonstrated excellent agreement in the assessment of trunk alignment (PEA 100%). Previous work supports these findings demonstrating good inter and intrarater reliability in the visual assessment of trunk flexion (Barker-Davies et al., 2018) and excellent reliability in the measurement of lateral trunk movement (Dingenen et al., 2013). In conjunction with knee valgus, lateral trunk position has been shown to correlate with peak external knee abduction moment during a single-leg drop vertical jump (Dingenen et al., 2013), this may have ramifications in both injury risk mitigation and performance in the sporting populations and therefore reinforces the value of this assessment in athlete profiling.

A limitation of this study was the use of 2D video to capture SL squat performance, as in clinical practice greater variance of movement may be expected across multiple planes. Dawson & Herrington (2015) did however find strong reliability when assessing real-time verses video analysis. Two-dimensional capture of frontal plane movements may not accurately reflect 3D kinematics as it is difficult to measure sagittal plane and rotational movements (Ageberg et al., 2010; Willson et al., 2006). Although video analysis has limitations, 2D projection angles have been shown to correlate with 3D analysis (McLean et al., 2005) and provide strong criterion validity (Herrington & Munro, 2014). Two-dimensional video analysis is a cost effective and practical alternative to complex motion analysis, which is appropriate for an elite sporting environment.

Another limitation of the present study is the protocol used for execution of the single-leg squat. Positioning the free, non-weight bearing leg, behind the body, has been shown to produce greater anterior pelvic tilt and contralateral pelvic drop (Khuu et al., 2016). Several studies have shown limitations in the ability to accurately assess pelvic motion during SL squat task (Barker-Davies et al., 2018), therefore, prescribing an alternative limb position may have reduced the requirement in this area. As the SL squat protocol was standardised for all participants, leg positioning should not affect the reliability of the assessment.

4.4.5 Conclusion

The findings of the present study show the single leg loading qualitative assessment tool, or QASLS, has excellent intrarater reliability in the identification of biomechanical inefficiencies during a SL squat. The dichotomous scoring of individual body segments showed substantial to excellent reliability, with only pelvic motion showing less than excellent results. This was in part due to the limitations imposed by 2D video analysis. Assessment findings relating to pelvic motion should therefore be interpreted with caution. In conclusion, the findings support the use of the QASLS in future research for profiling the lower limb.

4.5 Hand-Held Dynamometry: Reliability of frontal plane hip strength

Hip strength is an important component in the clinical assessment of the hip and groin (Reiman & Thorborg, 2014). Weakness is often a feature in a variety of hip related pathologies including FAIS (Casartelli et al., 2011; Kierkegaard et al., 2017), osteoarthritis (Loureiro et al., 2013) and adductor strains (Tyler et al., 2010). It has been suggested that hip strength plays an important role not only in injury rehabilitation, but also in the management of injury risk in the sporting context (Nadler et al., 2000; Tyler et al., 2010). The ability to easily and effectively measure hip strength, via methods which are valid and reliable are imperative, in both the clinical performance setting and research laboratory.

Isokinetic dynamometry (ID) is deemed as the ‘gold standard’ method for strength assessment but is associated with signficant time and cost implications which limits its usability (Chamorro et al., 2021; Stark et al., 2011). Hand-held dynamometry (HHD) is a portable device which is inexpensive and easy to administer (Maffiuletti, 2010; Thorborg, Petersen, Magnusson & Hölmich, 2010). Although muscles rarely function isometrically in daily activity, isometric strength has a strong predictive relationship to functional activity (Sapega, 1990) and is believed to be effective in detecting strength changes (Maffiuletti, 2010). Isometric assessment with a HHD has been shown to have good reliability and validity for strength and power in the lower limb (Mentiplay et al., 2015). The concurrent validity of HHD in relation to ID has been found to be very high for hip adduction, with a low reported limit of agreement (Chamorro et al., 2017), and with a high correlation for abduction (Kawaguchi & Babcock, 2010). The same level of validity is not seen for other lower limb joint comparisons (Chamorro et al., 2017). The aim of this study was to establish the intra and interrater reliability of the HHD in the assessment of hip abduction and adduction in the side lying position, which is currently clinical practice in GBRT.

4.5.1 Method

4.5.1.1 *Participants*

A convenience sample of eight elite rowers (6 females), age 26 ± 3 years, stature 181 ± 9 cm, body mass 77.7 ± 12.6 kg, volunteered for the study. Participant characteristics are presented in Table 4-14. Inclusion criteria for the study required participants to be between the ages of 18 and 35 years of age, with no history of lower limb injury for the preceeding 3 months.

All participants gave written informed consent to participate in the study. The project was approved by the University of Salford Reasearch ethics committee (ref: HSR1819-049).

Table 4-14: Participant characteristics

	Males		**Females**	
Characteristic	**Mean ± SD**	**95% CI**	**Mean ± SD**	**95% CI**
Age (years)	27 ± 2	24 – 9	26 ± 3	24 – 8
Body Mass (kg)	99.2 ± 1.1	97.7 – 100.6	77.7 ± 12.6	69.0 – 86.4
Stature (cm)	190 ± 6	180 – 199	181 ± 9	175 – 187
Leg Length (cm)	102 ± 3	98 – 101	97 ± 5	94 – 1.01

Standard deviation, SD; Confidence intervals, CI. N = 8

4.5.1.2 *Procedure*

On arrival at the test location, stature, body mass and leg length measurements were collected as described in section 3.1. Activity levels and current injury status were established through face-to-face interviewing.

Interrater reliability was conducted by two testers (B.S. & N.C.) who had a combined 12 years of experience working in elite sport collection strength diagnostics. The protocol for hip abduction and adduction strength is described in section 3.6. Each participant was assessed using both the supine and side lying methods. The testing order, for both starting position and rater, were randomised for each participant in order to limit systematic bias and raters were blinded to each others scores. Participants carried out 3 trials in each position and were given 30 – 60 seconds rest after each trial. They were given a minimum of 5 minutes rest between each assessment block. To alleviate the effects of fatigue, rest periods were prescribed between trials and test positions as recommended by several papers (Maffiulietti, 2010; Thorborg et al., 2010).

For intrarater reliability, the assessment was repeated one week later by tester 1 (B.S) at the same time point to negate the effects of diurnal variation. Participants were instructed not to change their daily routines and activity levels prior to each testing point. The study was completed during the general preparation training period at the beginning of the season. Consequently, weekly training volumes were consistent with predominant low training intensities. At the time of second assessment, the rater was blinded to the scores from the intital round of testing.

4.5.2 Statistical analysis

All data was collected in Newtons (N) and converted to torque (Nm) then normalised for body mass (Nm/kg) in order to allow comparison across athletic populations, as described in section 3.6. Mean values across 3 tests were calculated along with standard deviations (SD) and 95% confidence intervals (CI) for both hip abduction and adduction.

In order to ascertain intrarater reliability of the HHD assessment, data was analysed using the intraclass coefficient model ($ICC_{3,1}$) (Shrout & Fleiss, 1979). For interrater reliability, $ICC_{2,k}$ was used for analysis (Shrout & Fleiss, 1979). Standard error of measurement (SEM) and minimal detectable change (MDC) are also reported to reflect precision (Weir, 2005) and clinical signficiance (Haley & Fragala-Pinkham, 2006) of the data and to ensure any changes detected are not down to chance. The following formulas were utilised:

$$SEM = SD \times \sqrt{(1 - ICC)}$$

$$MDC = SEM \times 1.96 \times \sqrt{2}$$

For all ICC values, the criteria suggested by Portney & Watkins (2000) was used for interpretation:

Poor reliability	< 0.5
Moderate reliability	0.5 – 0.75
Good reliability	0.75 – 0.9
Excellent reliability	>0.9

4.5.3 Results

Intrarater reliability for hip strength in side lying, assessed using a HHD was moderate to excellent (ICC 0.71 - 0.92). The interrater reliability was moderate to good (ICC 0.73 -0.86). Full results are presented in Table 4-15 and Table 4-16.

Table 4-15: Isometric hip adduction/abduction strength descriptive data

	Abduction			**Adduction**		
	R1	**R2**	**R3**	**R1**	**R2**	**R3**
Mean ± SD (Nm/kg)	2.33 ± 0.35	2.54 ± 0.31	2.28 ± 0.36	2.22 ± 0.44	2.23 ± 0.52	2.56 ± 0.34
95% CI	2.06 - 2.61	2.29 – 2.79	1.99 – 2.56	1.87 – 2.57	1.81 – 2.65	2.29 – 2.82

Round 1, rater 1, R1; Round 2, rater 2, R2; Round 3, rater 1 R3; Standard deviation, SD; Newton-metres per kilogram, Nm/kg; Confidence interval, CI. N = 8

Table 4-16: Intrarater and interrater reliability of hip strength assessments

	Intrarater		**Interrater**	
	Abd	**Add**	**Abd**	**Add**
ICC	0.85	0.92	0.79	0.80
(95% CI)	(0.49 – 0.96)	(0.72 – 0.98)	(0.36 – 0.94)	(0.35 – 0.94)
%SEM	5.5%	5.8%	5.6%	8.1%
%MDC	15.2%	16.1%	15.6%	22.3%

Intraclass coefficient (ICC) values with 95% confidence intervals (CI), percentage standard error of measurement (%SEM) and percentage minimal detectable change (%MDC) for mean hip strength (Nm/kg).

4.5.4 Discussion

The results of this study demonstrate that a hand-held dynamometry assessment has moderate to excellent reliability in the collection of isometric hip adduction and abduction strength.

When analysing mean strength values, correlation coefficients for intrarater reliability in this study were comparable to that previously reported in the assessment of healthy individuals in a side lying test position (Krause et al., 2007; Martins et al., 2017) as well as in the assessment of those with pathology (Y.-H. Pua et al., 2008). Reliability was also shown to be better than some previous literature (Kawaguchi & Babcock, 2010; Scott et al., 2004; Thorborg et al., 2010) although lack of homogeneity in test procedure with respect to participant stabilisation or dynamometer fixation makes true cross study comparison difficult.

Between tester reliability was also shown to be good (ICC 0.79 - 0.80) which is supported by previous research (Arnold et al., 2010; Kelln et al., 2008; Krause et al., 2007). This should however be interpreted with caution as wide confidence intervals infer intrarater reliability may be poor to excellent. This may reflect the small study sample size. As a consequence, single tester collection is preferable. Martins et al., (2017) reported higher levels of intrarater reliability than found here, however they used a belt-stabilised HHD technique which may have increased test accuracy. Despite this, they reported higher percentage SEM. Clinical precision measures were acceptable in this current study with %SEM of 5.5% to 8.1%. These are similar to those reported by Mentiplay et al., (2015) who alongside good to excellent reliability, reported large effect sizes when assessing hip abduction and adduction and good to excellent validity when comparing a HHD to an ID.

Thorborg et al., (2010) found frontal plane hip strength to be superior when tested in a supine position compared to side lying although both positions were found to have moderate to good test-retest reliability. The error measurements reported for their side lying assessment were higher than those reported in the current study. This may reflect the differences in participant stabilisation. In this study, participants were externally stabilised whereas Thorborg et al., (2010) used a self-stabilsation method whereby participants held on to the table during testing which may have affected test reliability.

As the protocol is being developed for elite athletes, identification of optimal force production is important. Assessment of hip abduction in side lying has been found to produce significantly greater force magnitudes when compared with supine lying or standing (Widler et al., 2009). In the supine test position, Widler et al., (2009) observed lower electromyographic (EMG) activity in the Gluteus Medius of the tested leg, and the higher EMG activity in the contralateral leg. This infers sub-maximal motor recruitment in the limb being assessed when testing in this position which refutes the nature of an MVC assessment (Widler et al., 2009). Both intra and interrater reliability of the current method has been found to be comparable to other studies utilsing a supine test position (Ieiri et al., 2015; Kelln et al., 2008; Mentiplay et al., 2015), further supporting the use of this test procedure.

Krause et al., (2007) found when testing adduction strength, stabilising the non-test leg on a bench increased ICC from 0.79 to 0.89. This test position was equivalent to the one used in the present study which may have enhanced test reliability as it is known that the more unstable a participant is, the less able they are to produce force and hence the greater the risk of measurement variation (Krause et al., 2007).

Examiner strength has been shown to affect the reliability of HHD assessment (Lu et al., 2007) especially when the strength of the muscle group being tested exceeds the strength capabilities of the tester (Agre et al., 1987; Kelln et al., 2008; Thorborg et al., 2013). Scott et al., (2004) compared hip strength assessment of the HHD to a dynamic anchoring station (DAS) and found both strength output and reliability to be greater using the DAS when considering hip abduction. This mirrors the greater hip abduction magnitudes reported by Kramer, Vaz & Vandervoort, (1991). The latter study found that participants produced 35% more hip abduction torque when the dynamometer was fixed by a belt rather than an examiner. Kelln et al., (2008) has recommended that when muscle strength is obviously above the strength of the tester, HHD assessment should not be indicated. In the set-up position used for this study, the participant was stabilised by the plyometric boxes and the tester was placed at a mechanical advantage by kneeling over the person being tested. This has been shown to enhance test reliability (Kelln et al., 2008). A limitation of this study is not externally stabilising the HHD. However, assessors for hip strength data were physiotherapists and strength & conditioning coaches who were frequently exposed to strength training, as well as regularly collecting data using this method. This method was chosen as it is common practice currently within this cohort.

A make-test was performed in this study instead of a break-test, which may be considered a limitation. Make-tests have been shown to have greater reliability than break-tests (Schmidt et al., 2013) although eccentric break-tests are known to produce greater strength outputs (Bohannon, 1988). Isometric strength assessment induces less stress on the musculoskeletal system than eccentric muscle contractions and are therefore associated with a lower risk of injury (Hébert et al., 2011). An aim of the thesis is to develop a battery of screening tools to identify any risks of developing HRP in an elite sporting population, therefore a method associated with a lower injury risk is preferred.

Another consideration is whether the set-up position facilitated optimal force production. The protocols for each assessment specified that the hip joint was maintained in hip joint neutral, in all planes of motion, yet it is known that peak abductor torque occurs at around 10° adduction (Neumann, 2010). Furthermore, optimal adduction force is believed to occur between 6° and 50° abduction and varying degrees of hip flexion-extension depending on which adductor is being biased (Garcia et al., 2016). Accuracy of force production will have significant implications when considering agonist-antagonistic ratios and their potential relationship to hip health.

4.5.5 Conclusion

The use of a HHD in the collection of hip abduction and adduction strength is reliable between testers and between repeated tests. Reliability may be enhanced through the external fixation of the device. However, reproducibility was found to be moderate to excellent without this. Therefore, as this is the protocol currently used in working practice with the target demographic, reliability is sufficient to use this protocol for the remainder of the thesis while acknowledging its potential limitations.

4.6 Summary

This chapter investigated the reliability of a series of assessments that will be used in the remainder of the thesis. The reliability studies were all conducted using a sample of convenience, which is a limitation. Table 4-17 summarises the findings and considerations from this work.

Table 4-17: Summary of reliability studies

Test	Taken forwards	Considerations
Hip Internal Rotation using Easyangle®	✓	High levels of intra and interrater reliability
2D analysis of double-leg squat:		
Squat depth	✓	Excellent intrarater reliability for squat depth, knee, and ankle kinematics.
Knee, ankle kinematics	✓	
Pelvic kinematics	✗	Pelvic kinematics demonstrated poor reliability.
Y-balance Test Kit™	✓	YBT demonstrated excellent reliability in all directions whereas mSEBT had only moderate reliability in the anterior direction.
mSEBT	✗	
QASLS for Single-leg squat	✓	Scoring of individual body segments showed substantial to excellent reliability, with only pelvic motion showing less than excellent results
Hip strength using HHD:		
Abduction	✓	Moderate to excellent intrarater reliability. Interrater reliability showed acceptable reliability but with a wide confidence interval therefore single tester collection is preferable.
Adduction	✓	

CHAPTER 5

5 THE RELATIONSHIP BETWEEN PHYSICAL SCREENING CHARACTERISTICS AND PREVIOUS HIP-RELATED PAIN IN ELITE ROWERS.

The reliability of a battery of assessments measuring different physical characteristics were investigated in Chapter 4. This was completed to ensure that reproducible assessments are utilised during the experimental chapters and that any data obtained can be interpreted with precision and significance, both statistically and clinically. Establishing reliability is an important prerequisite in establishing test validity (Batterham & George, 2003; George et al., 2003).

In this chapter, the aim is to identify, and validate, a relationship between potential intrinsic risk factors for history of hip-related pain (HRP) in an elite rowing population. The objectives are: (1) to evaluate whether modifiable physical screening characteristics differ between rowers with and without a history of HRP, and (2) to ascertain whether the identified variables have the validity to discriminate between elite rowers with and without a history of HRP.

5.1 Introduction

There is a wealth of literature available pertaining to the anthropometric (Bourgois J et al., 2001; Bourgois et al., 2000; Jürimäe et al., 2000; Kerr et al., 2007; Mikulic, 2008; Russell et al., 1998; Slater et al., 2005), strength (Russell et al., 1998; Secher, 1993) and physiological (Fiskerstrand & Seiler, 2004; Ingham et al., 2002; Jürimäe et al., 2000; Russell et al., 1998; Secher, 1993; Steinacker, 1993) characteristics of elite rowers and their relationships with successful 2,000 m performance. Data relating to sports specific biomechanical profiles are also readily available (Buckeridge et al., 2015; McGregor et al., 2004) with a distinct understanding of their role in rowing-related low back pain (Nugent et al., 2021). There is however, limited research available on the physical characteristics in elite rowers, in relation to performance and/or health. Identifying modifiable factors, which may contribute to the occurrence of injury, is imperative to develop an understanding of injury causation and prediction (van Mechelen et al., 1992) and to inform possible targets for preventative interventions (Riley et al., 2013). These modifiable factors may include physical qualities such as strength, range of movement and movement control.

In a group of 76 international rowers, Newlands (2013) found that there was no relationship between a movement competency screen (MCS) and previous low back pain. The MCS is a 5-component tool with a qualitative scoring system. A higher composite score, theoretically equating to better movement execution, showed rowers were 1.58 times more likely to develop LBP compared to those with a lower score, although this finding was not significant. These findings are in disagreement with Clay et al., (2016), who using a similar screening tool, the Functional Movement Screen^{TM} (FMS^{TM}), demonstrated that female collegiate rowers with lower scores had a higher likelihood of sustaining LBP. Although the MCS and FMS^{TM} tasks include a double-leg (DL) and single-leg (SL) body weight squat, the methodologies are vastly different to those described in Chapter 3. Furthermore, the lack of quantitative insight into the kinematics of these two movements means comparison is not possible. A further limitation of both these studies, is that the screening was only conducted once at the start of the season. This doesn’t take into consideration that modifiable intrinsic risk factors such as strength and flexibility, are likely to vary throughout a typical periodised rowing season, therefore isolated assessment may not identify risks that are changeable and fluctuate frequently through a season (Meeuwisse et al., 2007).

Two additional studies have conducted musculoskeletal screening in rowers as part of a multi-dimensional intervention study investigating LBP in adolescents (Perich et al., 2011; Thorpe, 2009). Screening included: a qualitative assessment of lumbar spine motion during a DL squat, and an isometric squat hold to assess lower limb endurance. These studies failed to provide specific assessment details or results. Both studies reported an association between LBP and deficits in isometric squat hold duration. They also found a reduction in pain levels (Perich et al., 2011; Thorpe, 2009) and prevalence of LBP (Thorpe, 2009) across a rowing season following individually prescribed exercises based on screening findings.

To the authors knowledge, only one cross-sectional observational study has specifically profiled the hip joint in rowers. In 20 elite rowers, Wedatilake et al., (2021) found a significant, negative, correlation between hip joint internal rotation and degenerative disc disease (assessed via Pfirrmann score on 3T MRI) and cam morphology (as assessed via alpha angle on 3T MRI). The latter substantiates the findings in Chapter 2 of this thesis. Fifty percent of this cohort reported historical hip/groin pain at some stage during their rowing career, although no association between patient reported outcomes and clinical examination were reported.

To date, there are conflicting results between musculoskeletal screening and its association with previous injury in several other sports/physically active groups. Linek et al., (2019) investigated the relationship between Y-balance test (YBT) and previous hip and/or groin pain in adolescent professional footballers (mean age 15.6 years). The study found that composite scores, alongside posterior-lateral (PL) and posterior-medial (PM) components, were lower in the symptomatic group, despite most of the group being classified as having minor symptoms. These findings were not supported by Chimera et al., (2015) who found no association between isolated or composite YBT scores and previous hip injury, or any injury, in Division 1 college athletes (mean age 20 ± 1 years). Similarly, there are inconsistent results between FMS^{TM} and its association with previous injury. Peate et al. (2007), after adjusting for age, found that fire-fighters were 1.68 times more likely to fail FMS^{TM} assessment if they had a history of work-related injuries. However, Schneiders et al., (2011) reported no significant difference in FMS^{TM} composite score in young physically active individuals, with or without an injury in the previous six months. Neither study disclosed information regarding the types of injuries accounted for, which limits the ability to compare or further interpret their findings.

Chimera et al., (2015) found collegiate athletes with a history of hip pain performed worse during the FMS^{TM}, specifically during a deep squat and a hurdle component of the assessment. Linek et al., (2019) found no difference in FMS^{TM} scores in adolescent footballers with and without active hip and/or groin symptoms. The conflicting findings relating to screening and prior history of injury may be partly explained by the variations in study participants with respect to age, activity, and sex. Sex differences have previously been identified in individuals with FAIS driven HRP during tasks such as gait (Lewis, Khuu, et al., 2018), stepping (Lewis, Loverro, et al., 2018) and balance assessments (Freke et al., 2018) this therefore warrants further consideration when planning and investigating a screening tool.

Hip strength assessments are advised for athletes with, or at risk of, hip and groin related problems (Thorborg et al., 2011) and are frequently reported to be reduced in individuals with HRP as discussed in Chapter 2. Mosler et al., (2016) reported an association between eccentric hip adductor strength and risk of hip/groin injuries in professional football players. Other than previous injury, the study also found neither screening tests nor bony morphology to be associated with injury risk around the hip and groin. An association between previous hip-groin injury and risk of injury has been suggested (Weir et al., 2015), although much of this research does not relate specifically to hip-joint related groin pain (Whittaker et al., 2015).

There is currently a gap in the literature relating to the physical characteristics of elite rowers. Specifically, the role that movement qualities and physical characteristics may play in injury aetiology or prediction. Understanding normal values in this unique population, using reliable tests with low error measurement, is essential. Furthermore, a retrospective analysis into their potential association with injury history, may advance the understanding of the determinants of hip-related pain (HRP) in elite rowers.

The assessments taken forwards into this screening study are based on the literature synthesized in Chapter 2, which is limited in elite rowers. This is supported by the recent recommendations taken from the IHiPRN who support including further clinical research into squat depth, single-leg tasks, muscle function and range of movement (Mosler et al., 2019).

5.1.1 Aims

The primary aim of this chapter is to establish whether lower limb screening assessments are different between rowers with, and without a history of HRP.

It is hypothesised that rowers with a history of HRP, will present with a reduction in squat depth, hip strength, hip range of movement, and reach distances when performing a YBT, when compared to rowers with no history of HRP. It is also hypothesised that components of the QASLS scoring system, which consider hip adduction and pelvic position, will correlate with HRP, but that composite score will not.

A secondary aim of this study is to determine the construct (known group) validity of a series of assessments in identifying rowers with a history of HRP, compared to those who have not.

5.1.2 Objectives

The objectives of this chapter are to determine:

- The differences between rowers with, and without, a history of HRP within the following physical characteristics:
    - Passive hip internal rotation range of movement.
    - DL squat depth, and its associated kinematic variables.
    - Isometric hip adduction/abduction strength, including frontal plane strength ratios.
    - Y-balance test.
    - SL squat, both composite and individual scores.
- Which assessments, have validity in distinguishing between rowers with, and without, a history of HRP. This includes establishing optimal thresholds for identified assessments.

The results from this chapter will be utilised to develop a prospective screening tool for the subsequent studies of the thesis.

5.2 Methodology

5.2.1 Study Design and Participants

Screening data from 68 elite rowers (male = 32, female = 36), from the Great Britain Rowing Team senior squad, was retrospectively analysed. The majority of the cohort was classified as Tier 5: World Class, as per the classifcation framework proposed by McKay et al., (2021).

Each individual was supplied with a participant information sheet (see appendix 10.2) and written informed consent was obtained (see appendix 10.3). Participants were excluded if they had: a current lower limb or back injury or any medical condition which may affect the assessment, or if they presented with other causes of hip and/or groin pain (Figure 1-5) (Weir et al., 2015). Eligibility criteria and current health status were established through face-to-face interviewing. For rowers that were injured at the time of data collection, a risk assessment was conducted in conjunction with their medical practitioner to ensure only safe and apppropriate tests were completed. Once eligibility criteria was applied (see Figure 5-1), 67 rowers were taken forward. The study received ethical approval from the University of Salford Research ethics committee (ref: HSR1819-049). Participant characteristics are outlined in Table 5-1.

Table 5-1: Participant characteristics

	Control (n=32)				**HRP (n=35)**			
	Males		Females		Males		Females	
	Mean ± SD	**95% CI**	**Mean ± SD**	**95% CI**	**Mean ± SD**	**95% CI**	**Mean ± SD**	**95% CI**
Age (years)	26 ± 2	25 – 27	27 ± 3	25 –- 29	28 ± 3	25 – 31	26 ± 3	25 –- 27
Sex (n)	18		14		14		21	
Body Mass (kg)	88.3 ± 9.3	83.2 – 93.4	74.9 ± 2.2	73.2 – 76.5	99.2 ± 6.7	93.3 – 105.1	74.2 ± 6.8	71.3 – 77.2
Stature (cm)	190.3 ± 6.3	186.9 – 193.8	179.7 ± 3.9	176.8 – 182.6	195.6 ± 4.5	191.6 – 199.6	178.6 ± 5.6	176.2 – 181.0
Leg Length (cm)	100.0 ± 6.0	96.6 – 102.9	96.1 ± 3.3	93.6 – 98.5	102/4 ± 2.1	100.6 – 104.2	95.3 ± 4.6	93.4 – 97.3

SD, Standard deviation; CI, Confidence intervals; kgs, kilograms; cm, centimetres.

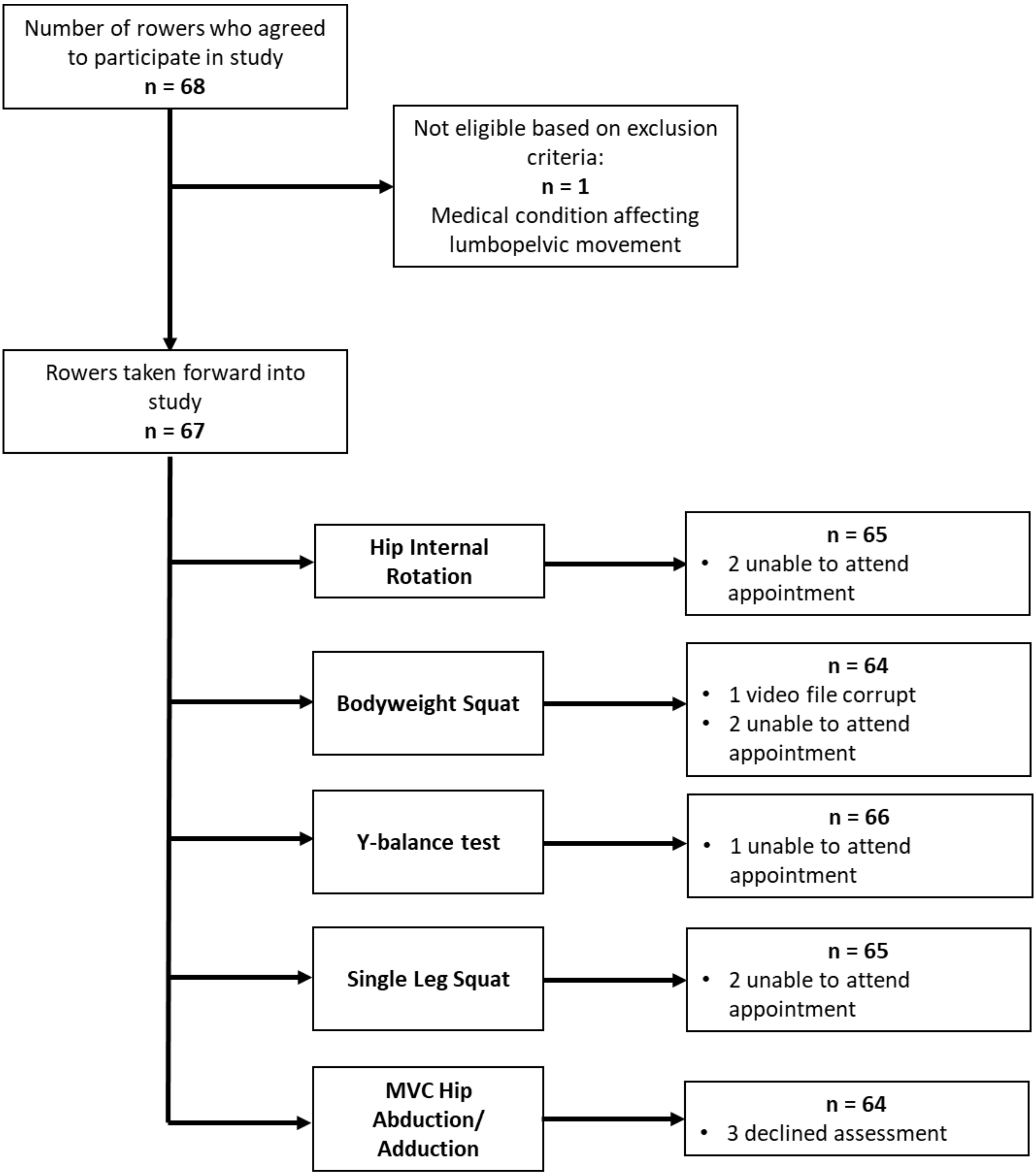


Figure 5-1: Eligibility for study

5.2.2 Musculoskeletal Screening Procedure

Each participant underwent six physical assessments: 1) passive hip internal rotation, 2) body weight double-leg squat, 3) the Y-balance test, 4) single-leg squat, 5) isometric hip abduction and adduction strength. The methods are described fully in the General Methods Chapter 3. Screening was conducted within a two-week period, at the start of season (general preparation phase 1; see Figure 6-1) to accommodate the training programme requirements of the rowers.

Practitioners embedded fully within the Great Britain Rowing Team (LS, NC, SL, BS, SBL) assisted in the collection of hip strength data. The interrater reliability of this method was shown to be good to excellent (ICC 0.88- 0.99). All other screening was completed and retrospectively analysed by the lead author. The reliability of which is reported in Chapter 4.

5.2.3 Injury Classificiation

For this retrospective study, rowers were classified into two groupings:

1. *Hip-related pain group*: those with a history of HRP
2. *Control grou*p: those without a previous history of HRP

Hip-related pain (HRP) was defined as motion or position-related pain or stiffness in the hip or groin as described by Dijkstra et al., (2023). Symptoms may also be experienced in the back, buttock, or thigh. In addition to pain and/or stiffness, patients may also describe clicking, catching, locking, restricted range of motion or giving way. Diagnosis was based on the clinical and physical examination described by Reiman and Thorborg (2014). The accuracy of these diagnostic tests was investigated in chapter 2.

The HRP group contained individuals who had experienced time loss injuries as well as those with no times loss from sports participation but requiring medical attention (Clarsen et al., 2013). This was done in order to establish the full burden of FAIS, as it is common for an elite athlete to continue to train and compete in the presence of FAIS, as the onset is frequently insidious and often symptoms are transient in nature (Philippon et al., 2007).

Rowers were grouped by the medical staff and injury history was validated using the athlete medical records, which are stored in the English Institute of Sports (EIS) Performance Data Management System (PDMS). Consent to access this information was obtained from the individual athlete involved (see appendix 10.3) and through organisational agreement from the English Institute of Sport (appendix 10.4) and British Rowing National Governing Body (appendix 10.5).

In cases where rowers had a history of bilateral HRP, the most symptomatic and/or functionally restricting limb, as identified by the participant, was used for analysis.

5.2.4 Data Analysis

Statistical analyses were performed using SPSS (version 26, IBM Corporation, New York, USA).

5.2.4.1 *Between group comparisons: HRP verses control group*

Descriptive statistics were collated and visualised for each data set, and reported as mean, standard deviation and 95% confidence intervals unless otherwise reported. All continuous data was assessed for normality using a Shapiro-Wilk test prior to any further analysis. Where parametric assumptions were met, a two-way analysis of variance (ANOVA) was used to detect differences between groups and sex respectively, with a *p*-value set at ≤0.05. For variables which were deemed non-parametric, a Kruskal-Wallis test was utilised. This only applied to the SL squat assessment and hip strength ratio.

5.2.4.2 *Univariate analysis*

To establish construct validity, assessments that demonstrated differences between groups, were taken forward to the second part of the study. Optimal cut-off thresholds were determined through Receiver Operating Characteristics (ROC) curves and through patterns identified via data visualisation. These thresholds were then used to ascertain clinical prediction rules: sensitivity (SN), specificity (SP), positive and negative likelihood ratios (PPV, NPV), positive and negative predictive values (+ve LR, -ve LR), and odds ratios (OR).

These were calculated using the number of true positives (positive assessment and history of HRP), false positives (positive assessment and control group (no HRP)), false negatives (negative assessment and history of HRP) and true negatives (negative assessment and control group (D.G. Altman & J.M. Bland, 1994; D.G. Altman & J.M Bland, 1994). The clinical prediction rules were calculated in the following way:

Test Outcome	**Condition**	
	Positive (HRP Group)	**Negative (Control Group)**
Positive	A (true positive)	B (false positive)
Negative	C (false negative)	D (true negative)

Sensitivity = A/(A + C)

Specificity = D/(B+C)

Positive predictive value = A/(A+B)

Negative predictive value = D/(C+D)

Positive likelihood ratio = Sensitivity /1- Specificity

Negative likelihood ratio = 1- Sensitivity /Specificity

Odds Ratio = (A/C)/(B/D)

For the individual scoring components of the QASLS assessment, percentage exact agreement (PEA) was calculated to ascertain the relationship between HRP and a positive or negative score.

5.2.4.3 *Multivariate analysis*

Risk prediction modelling is often poor when only singular prognostic factors are included, therefore multivariate analysis was conducted to explore the association between several screening assessments and history of HRP (Riley et al., 2013). This occurred via multivariate binary logistic regression as the outcome groups are dichotomous variables. To avoid overfitting and to ensure sufficient cases per independent variable, the number of assessments included in the model needed to be reduced. Assessments demonstrating *p* values < 0.1 and/or positive likelihood ratios >2 or negative likelihood ratios <0.5 on univariate testing were taken forwards (Mosler, Agricola, et al., 2018). Diagnostic analysis was performed to ensure the following assumptions were met:

- Removal of outliers: to ensure that the model is not influenced by a small number of cases, residuals with z-scores of >3.0 were treated as outliers and removed from the data set.
- Linearity of independent variables and log-odds.
- Absence of multicollinearity.

5.3 Results

Sixty-seven rowers met the inclusion criteria. One participant was excluded due a complex medical condition which impaired lumbopelvic motion, and therefore hindered lower body movement. There were no differences ($p > 0.05$) in age, body mass, stature, or leg length between rowers with and without HRP (see Table 5-1).

5.3.1 Between Group comparisons: HRP verses control group

5.3.1.1 *Hip Internal Rotation*

Data for 65 individuals was collected for the hip IR assessment. Two rowers were unable to attend the assessment at the specified time. Mean IR hip ROM for all rowers, male and female only are presented in Table 5-2. All data was normally distributed.

Table 5-2: Mean Hip Internal Rotation (°) ± SD (± 95% CI).

	Control	**HRP**
All rowers	40.4 ± 8.9 (37.2 – 43.3)	37.1 ± 10.5 (33.5 - 40.7)
Male	**36.4**$^{\psi}$ ± 6.2 (33.6 – 39.2)	**28.8**$^{\psi}$ ± 9.5 (25.6 – 32.1)
Female	45.5 ± 9.4 (40.6 – 50.4)	42.1 ± 7.8 (39.4 – 44.7)

*$^{\psi}$ Significant p-values < 0.05 are in **bold**; SD, standard deviation; CI, confidence interval. HRP, hip-related pain.*

Comparing HRP to the control group, there was a difference between group (*F* = 7.226, *p* = 0.009, n_p^2=0.106) and between sex (*F* = 29.693, *p* = <0.001, n_p^2=0.327). There was no effect group*sex interaction (*F* = 1.007, *p* = 0.320, n_p^2=0.016). Post hoc analysis found the difference was between male controls verses male HRP.

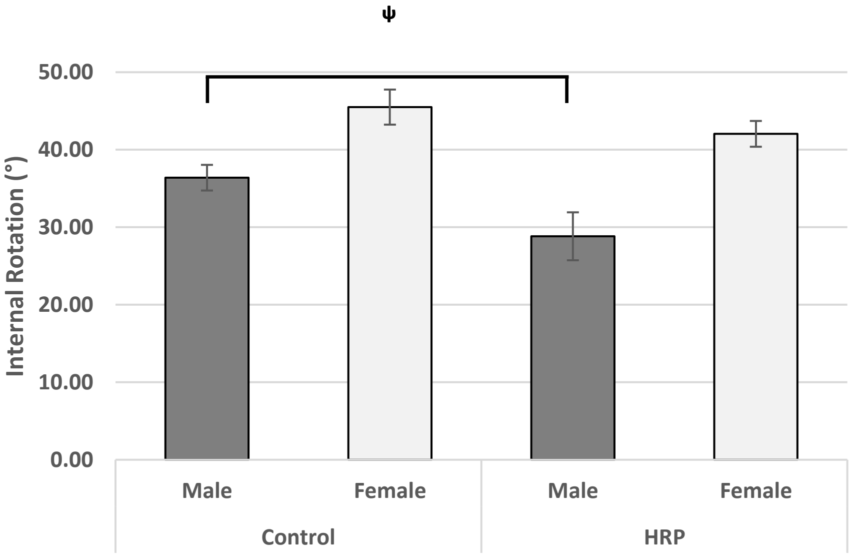


Figure 5-2 Hip Internal Rotation, between group comparisons

5.3.1.2 *Double-leg Squat*

Data for 64 individuals was collected for the DL squat assessment. Two rowers were unable to attend the assessment at the specified time. One participant was lost due to corrupted video data.

Two dimensional parameters for DL squatting are presented in Table 5-3 and Table 5-4. All metrics were normally distributed and met assumptions for a two-way ANOVA. There were no significant differences found between control or HRP groups (p >0.05) when considering frontal plane squat depth (Left: F = 1.44, p = 0.234, n_p^2=0.024; Right F = 1.46, p = 0.232, n_p^2=0.024) or for any other kinematic markers in either frontal or sagittal plane.

Although not significant, mean squat depths were higher in the group with a history of HRP. These differences were greater than the MDC reported in Chapter 4 (MDC 0.83 – 0.85%).

Table 5-3: Mean Squat Depth (%LL) ± SD (± 95% CI).

		Control	**HRP**
All rowers	**Left PSIS**	50.5 ± 6.9 (48.1 - 52.9)	52.5 ± 7.0 (49.8 - 55.5)
	Right PSIS	50.5 ± 6.9 (48.14 - 52.8)	52.5 ± 7.5 (49.8 - 55.4)
Male	**Left PSIS**	51.4 ± 6.3 (48.5 - 54.2)	53.2 ± 10.0 (47.3 - 59.1)
	Right PSIS	51.3 ± 6.2 (48.6 - 54.1)	53.1 ± 10.0 (47.2 - 59.0)
Female	**Left PSIS**	49.4 ± 7.7 (45.5 - 53.3)	52.2 ± 6.5 (49.5 - 54.94)
	Right PSIS	49.9 ± 7.7 (45.5 - 54.1)	52.2 ± 6.3 (49.6 - 54.9)

SD, standard deviation; CI, confidence interval. LL, leg length; HRP, hip-related pain; PSIS, posterior superior iliac spine.

Table 5-4: 2D squat kinematics (excluding %SQ depth from PSIS).

	SAGITTAL PLANE (LATERAL) View								FRONTAL PLANE (POSTERIOR) View	
	ST PELVIC ANGLE LEFT (°)	**ST PELVIC ANGLE RIGHT (°)**	**% SQ DEPTH LEFT GT**	**% SQ DEPTH RIGHT GT**	**KNEE ANGLE LEFT (°)**	**KNEE ANGLE RIGHT (°)**	**ANKLE ANGLE LEFT (°)**	**ANKLE ANGLE RIGHT (°)**	**LATERAL DRIFT (mm)**	**PELVIC OBLIQUITY (mm)**
Control	12.0 ± 8.0	11.2 ± 56.0	50.3 ± 5.7	50.4 ± 5.8	112.7 ± 10.6	104.7 ± 17.8	57.0 ± 4.5	57.2 ± 5.2	0.00 ± 0.02	0.00 ± 0.004
	(9.3 – 14.8)	(9.1 – 13.2)	(48.3 – 52.2)	(48.4 – 52.3)	(109.1 - 116.3)	(98.7 – 110.8)	(55.4 – 58.5)	(55.4 – 58.9)	(-0.004 – 0.01)	(-0.002 – 0.001)
HRP	12.0 ± 8.3	10.6 ± 7.5	52.0 ± 6.9	52.6 ± 7.2	109.9 ± 12.5	106.4 ± 15.2	56.9 ± 5.4	58.3 ± 5.5	0.01 ± 0.01	0.00 ± 0.01
	(9.1 – 14.8)	(8.1 – 13.2)	(49.6 – 54.5)	(50.1 – 55.0)	(105.5 -114.2)	(101.1 - 111.6)	(55.0 - 58.7)	(56.4 - 60.2)	(0.002 - 0.01)	(-0.002 - 0.002)

ST, standing; SQ, squat; GT, greater trochanter; PSIS, posterior superior iliac spine.

5.3.1.3 *Y-balance Test*

Data for 66 individuals was collected for the YBT assessment, including composite reach distances. One participant was unable to attend the assessment at the specified time.

Mean reach across three tests for all rowers are presented in Table 5-5. All data was normally distributed. No significant differences were detected between the control or HRP groups (p >0.05). Sex differences were seen during the PL and PM reach distances. In both instances males achieved superior reach distances (p <0.05).

Table 5-5: YBT Data, Mean Normalised reach ± SD (± 95% CI).

		Control	HRP
All rowers	**Anterior**	69.29 ± 6.07 (67.10 – 71.48)	67.94 ± 6.14 (65.80 – 70.08)
	Posterolateral	111.63 ± 7.95 (108.38 – 113.95)	110.75 ± 9.57 (108.88 – 114.32)
	Posteromedial	107.25 ± 8.79 (103.69 – 110.08)	107.67 ± 10.02 (105.20 – 111.45)
	Composite	288.09 ± 19.21 (280.42 – 294.25)	286.53 ± 21.31 (281.10 – 294.63)
Male	**Anterior**	68.68 ± 5.79 (65.78 – 71.58)	67.03 ± 6.05 (63.74 – 70.31)
	Posterolateral	114.88 ± 6.54 (111.21 – 118.56)	116.43 ± 6.63 (112.26 – 120.60)
	Posteromedial	109.80 ± 7.67 (105.57 – 114.02)	112.04 ± 9.91 (107.25 – 116.83)
	Composite	293.36 ± 16.36 (284.21 – 302.51)	295.50 ± 20.25 (285.12 – 305.87)
Female	**Anterior**	69.98 ± 6.56 (66.61 – 73.18)	68.86 ± 6.25 (66.11 – 71.61)
	Posterolateral	107.44 ± 7.92 (103.27 – 111.62)	106.77 ± 9.41 (103.28 – 110.26)
	Posteromedial	103.97 ± 9.32 (99.18 – 108.77)	104.62 ± 9.13 (100.61 – 108.63)
	Composite	281.31 ± 21.02 (270.94 – 291.69)	280.25 ± 20.19 (271.57 – 288.93)

SD, standard deviation; CI, confidence interval

5.3.1.4 *Single-leg Squat*

Composite results for 65 rowers who completed the SL squat are presented in Table 5-6. Two rowers were unable to attend the assessment at the specified time.

Data was shown to be non-parametric and was therefore analysed using a Kruskal-Wallis test. No between group difference was found for this assessment. Further analysis into the individual components of the QASLS assessment also found no differences.

Table 5-6: SL Squat: Mean Composite QASLS Score, ± SD (± 95% CI).

	Control	**HRP**
All rowers	3.49 ± 1.85 (2.91 – 4.11)	2.76 ± 1.85 (2.12 – 3.35)
Male	3.38 ± 2.08 (2.60 – 4.15)	2.61 ± 1.56 (1.91 – 3.92)
Female	3.64 ± 1.52 (2.72 – 4.57)	2.85 ± 1.60 (2.15 – 3.46)

SD, standard deviation; CI, confidence interval

5.3.1.5 *Isometric hip adduction/abduction strength*

Sixty-four rowers were analysed following assessment of hip strength. Three rowers withdrew consent for assessment due to a pending performance test. Isolated strength data was normally distributed and assessed using a two-way ANOVA. Hip strength ratios were non-parametric and assessed using a Kruskal-Wallis test. All data is presented in Table 5-7.

No between group differences were seen for isolated isometric hip adduction/abduction strength ($p > 0.05$). Between sex differences were seen for hip adduction strength ($p = <0.001$) with males producing greater outputs (M = 2.72 Nm/kg; F = 2.25 Nm/kg). No interaction effect was seen between group*sex.

Table 5-7: Mean Hip Strength, SD (±95% CI)

		Control	**HRP**
All rowers	**Abduction (Nm/kg)**	2.39 ± 0.33 (2.22 – 2.55)	2.44 ± 0.53 (2.27 – 2.61)
	Adduction (Nm/kg)	2.42 ± 0.51 (2.23 – 2.59)	2.48 ± 0.58 (2.38 – 2.74)
	Add:Abd Ratio	1.02 ± 0.23 (0.95 – 1.11)	1.07 ± 0.31 (1.04 – 1.22)
Male	**Abduction (Nm/kg)**	2.36 ± 0.31 (2.15 – 2.59)	2.46 ± 0.43 (2.24 – 2.59)
	Adduction (Nm/kg)	2.59 ± 0.56 (2.35 – 2.83)	2.85 ± 0.51 (2.57 – 3.14)
	Add:Abd Ratio	1.11 ± 0.27 (0.99 – 1.23)	1.30 ± 0.38 (1.15 – 1.45)
Female	**Abduction (Nm/kg)**	2.41 ± 0.36 (2.17 – 2.66)	2.43 ± 0.59 (2.23 – 2.62)
	Adduction (Nm/kg)	2.23 ± 0.36 (1.96 – 2.49)	2.26 ± 0.51 (2.05 – 2.48)
	Add:Abd Ratio	0.94 ± 0.14 (0.80 – 1.07)	0.95 ± 0.17 (0.85 – 1.06)

SD, standard deviation; CI, confidence interval; Nm/kg, newton-meters per kilogram

When comparing isometric hip adduction/abduction strength ratios, a significant difference was detected between groups (*p* = 0.009). Post hoc analysis revealed the differences seen were between sex (*p* ≤ 0.05) (see Figure 5-3)

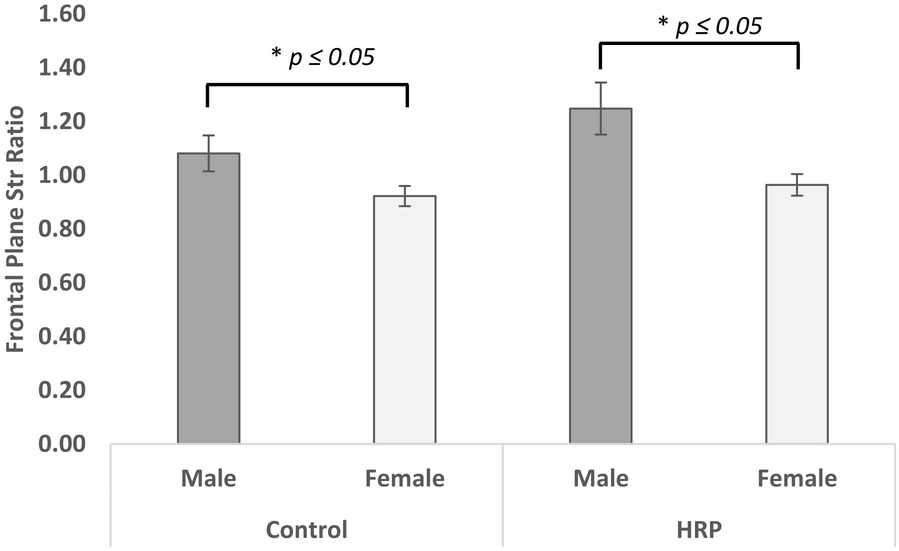
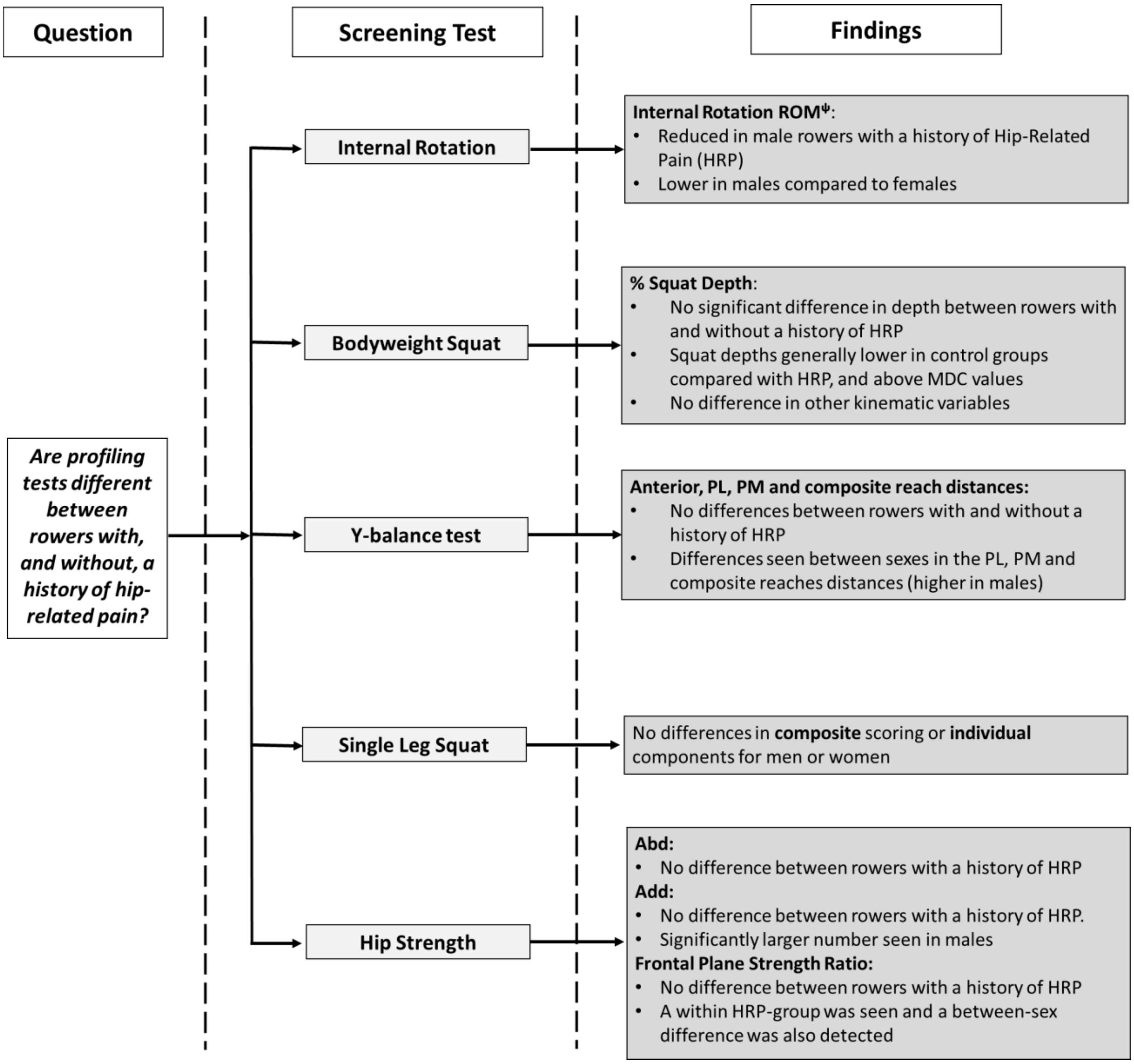


Figure 5-3: Hip Strength Ratio, between group comparisons

5.3.1.6 *Summary of Results*



Are profiling tests different between rowers with, and without, a history of hip-related pain?

Internal Rotation ROM$^{\psi}$:
- Reduced in male rowers with a history of Hip-Related Pain (HRP)
- Lower in males compared to females

% Squat Depth:
- No significant difference in depth between rowers with and without a history of HRP
- Squat depths generally lower in control groups compared with HRP, and above MDC values
- No difference in other kinematic variables

Anterior, PL, PM and composite reach distances:
- No differences between rowers with and without a history of HRP
- Differences seen between sexes in the PL, PM and composite reaches distances (higher in males)

No differences in **composite** scoring or **individual** components for men or women

Abd:
- No difference between rowers with a history of HRP

Add:
- No difference between rowers with a history of HRP.
- Significantly larger number seen in males

Frontal Plane Strength Ratio:
- No difference between rowers with a history of HRP
- A within HRP-group was seen and a between-sex difference was also detected

Figure 5-4: Summary of findings and next steps from 5.3.1

$^{\psi}$, $p \leq 0.05$; PL, posterolateral; PM, posteromedial; Abd, abduction; Add, adduction

5.3.2 Construct validity of screening relative to history of HRP

5.3.2.1 *Hip Internal Rotation*

The findings in section 5.3.1.1 allowed hip IR to be taken forward for further analysis. The data was visualised using box and whisker plots. No identifiable threshold was established for the complete group or for females (Figure 5-5 and Figure 5-6, respectively), this was verified using ROC curves.

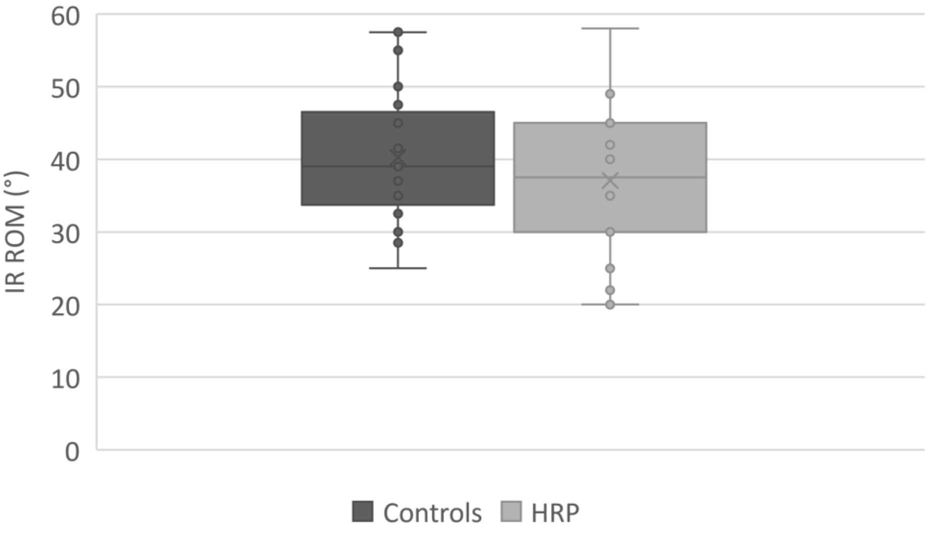


Figure 5-5: Box & whisker plot, all rowers hip IR ROM (°).

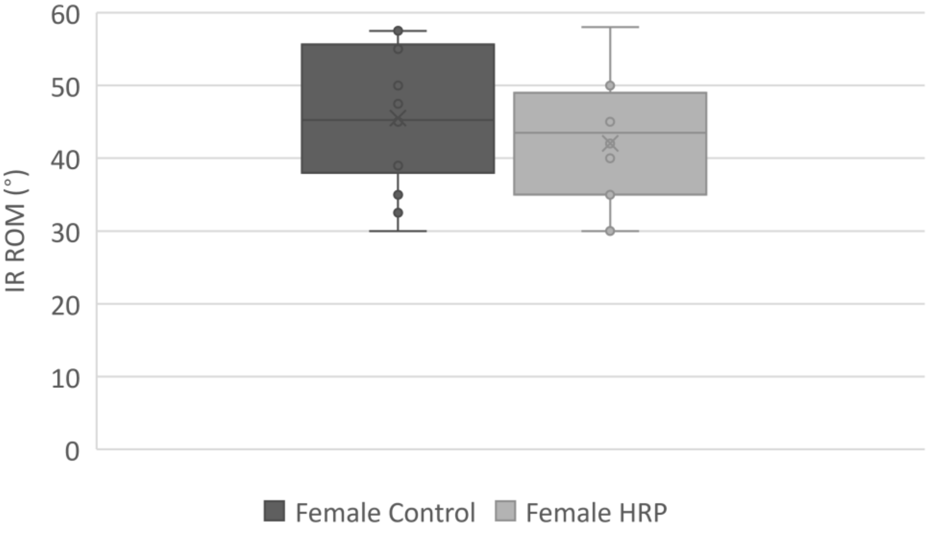


Figure 5-6: Box & whisker plot, female hip IR ROM (°).

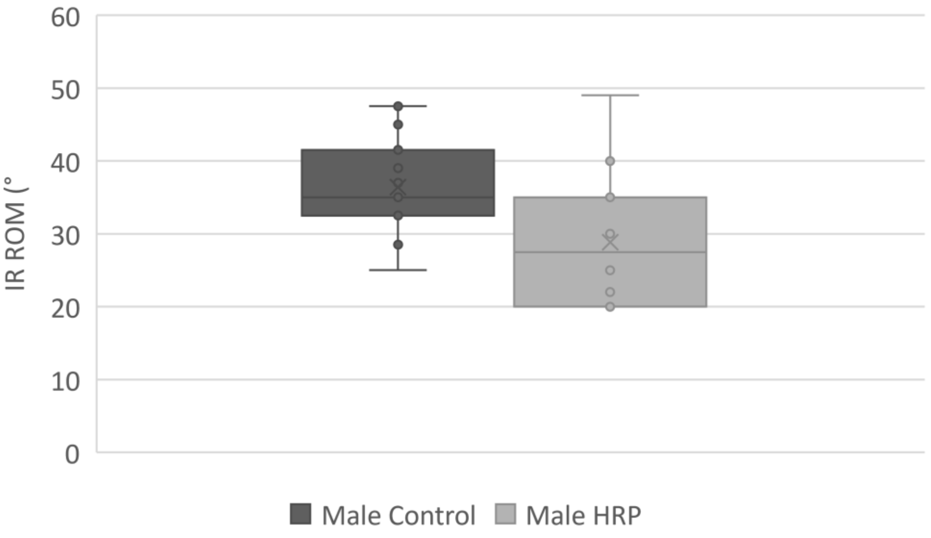


Figure 5-7: Box & whisker plot, male hip IR ROM (°).

When viewing male data in isolation (Figure 5-7), Hip IR $\leq$ 30° indicates a prognostic threshold producing sensitivity and specificity values of 0.67 and 0.84 respectively with an odds ratio 10.67 (95%CI 1.91- 59.62). Application of ROC curves, and resultant area under the ROC curve (AUC, 0.756) showed fair predictive ability of IR to classify those with a history of HRP. Assessment of clinical prediction is reported in Table 5-8 and Table 5-9.

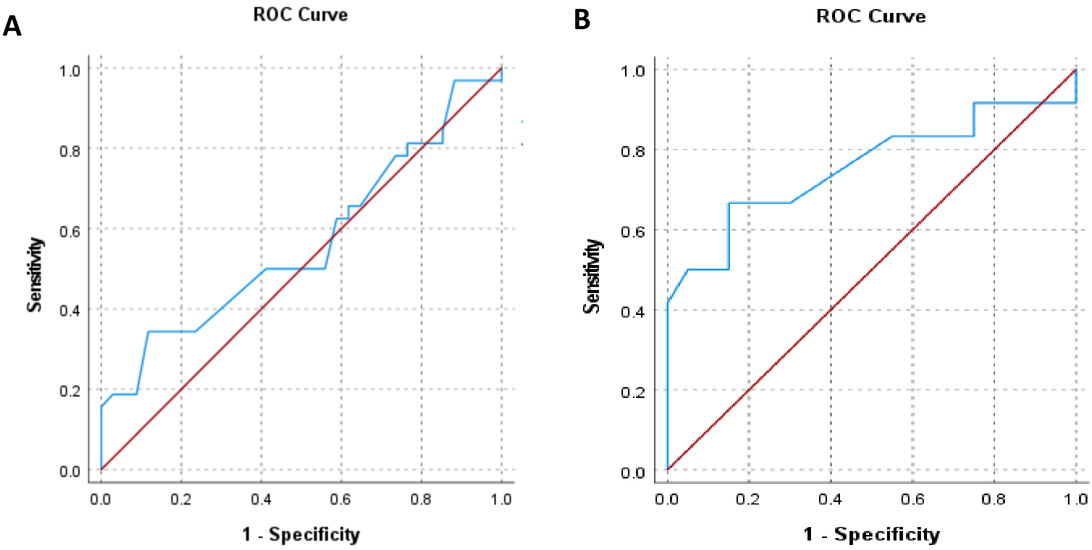


*Figure 5-8: ROC curve, hip IR (**A**) all rowers, (**B**) males.*

Table 5-8: All rowers hip IR ≤30°.

Test Accuracy Outcome	**HRP**
Sensitivity	0.34
Specificity	0.88
PPV	0.73
NPV	0.58
+ve LR	2.84
-ve LR	0.75
OR	3.80 (1.06 – 13.59)

PPV, positive predictive value; NPV, negative predictive value; +ve LR, positive likelihood ratio; -ve LR, negative likelihood ratio; OR odds ratio.

Table 5-9: Male hip IR <u><</u>30°.

Test Accuracy Outcome	**HRP**
Sensitivity	0.67
Specificity	0.84
PPV	0.73
NPV	0.80
+ve LR	4.22
-ve LR	0.40
OR	10.67 (1.91 – 59.62)

PPV, positive predictive value; NPV, negative predictive value; +ve LR, positive likelihood ratio; -ve LR, negative likelihood ratio; OR, odds ratio.

5.3.2.2 *Double-leg Squat*

The findings in section *5.3.1.2*, allowed squat depth assessed in the sagittal plane, to be taken forward for further analysis. The distribution of squat depth data presented graphically in Figure 5-9, showed squat depth of greater than 60% leg length (LL) as a potential cut-off score for prognostic purposes.

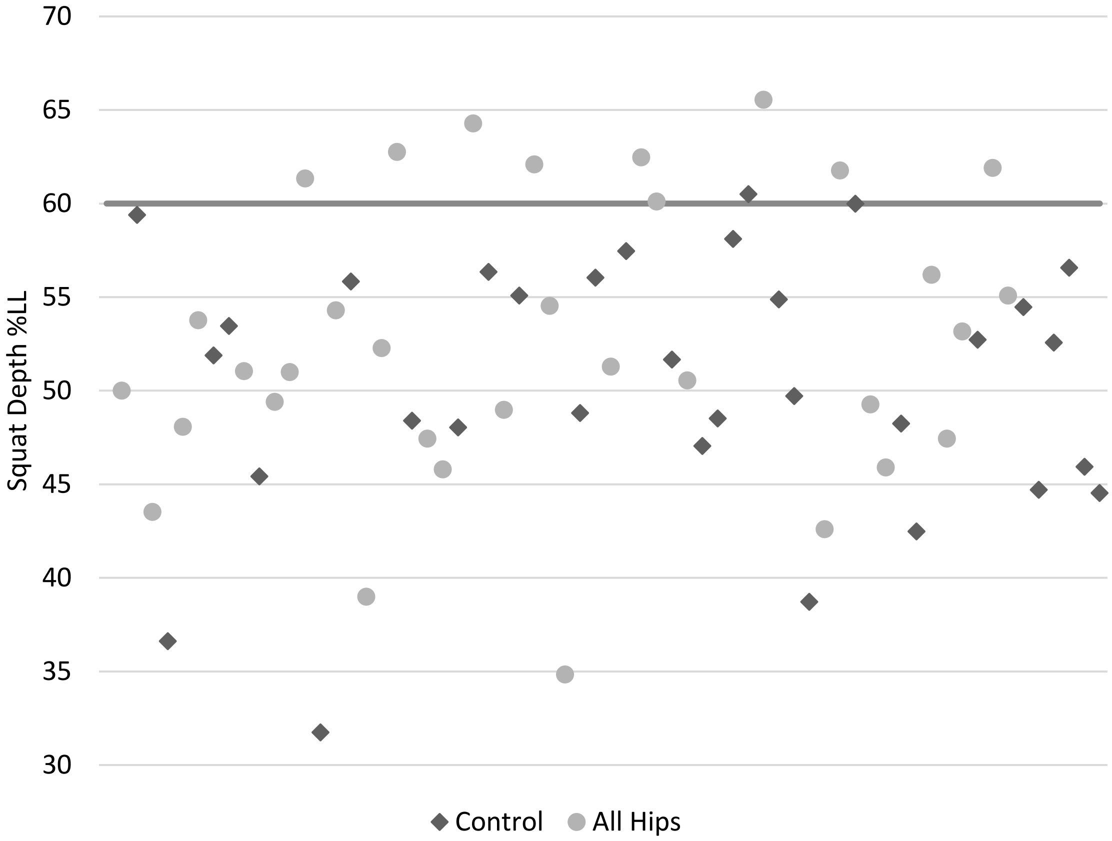


Figure 5-9: Scatter plot for squat depth of all rowers.

Full results for test accuracy are presented in Table 5-10 and Table 5-11. Area under the ROC curve analysis (AUC) showed the model quality to be poor (AUC 0.565).

Table 5-10: All rowers squat depth 60%.

Test Accuracy Outcome	HRP
Sensitivity	0.27
Specificity	0.97
PPV	0.90
NPV	0.56
+ve LR	8.73
-ve LR	0.72
OR	11.63 (8.87-14.38)

PPV, positive predictive value; NPV, negative predictive value; +ve LR, positive likelihood ratio; -ve LR, negative likelihood ratio; OR odds ratio.

Table 5-11: Male and female squat depth 60%.

Test Accuracy Outcome	Male HRP	Female HRP
Sensitivity	0.42	0.19
Specificity	0.89	1.00
PPV	0.71	1.00
NPV	0.70	0.45
+ve LR	3.75	-
-ve LR	0.53	0.81
OR	5.71 (3.46 – 7.97)	-

PPV, positive predictive value; NPV, negative predictive value; +ve LR, positive likelihood ratio; -ve LR, negative likelihood ratio; OR, odds ratio.

5.3.2.3 *Y-balance Test*

The findings in section 5.3.1.4, in conjunction with visual analysis of the YBT data (Figure 5-10), found no clear threshold for further analysis for the cohort or for sex-groups within the cohort.

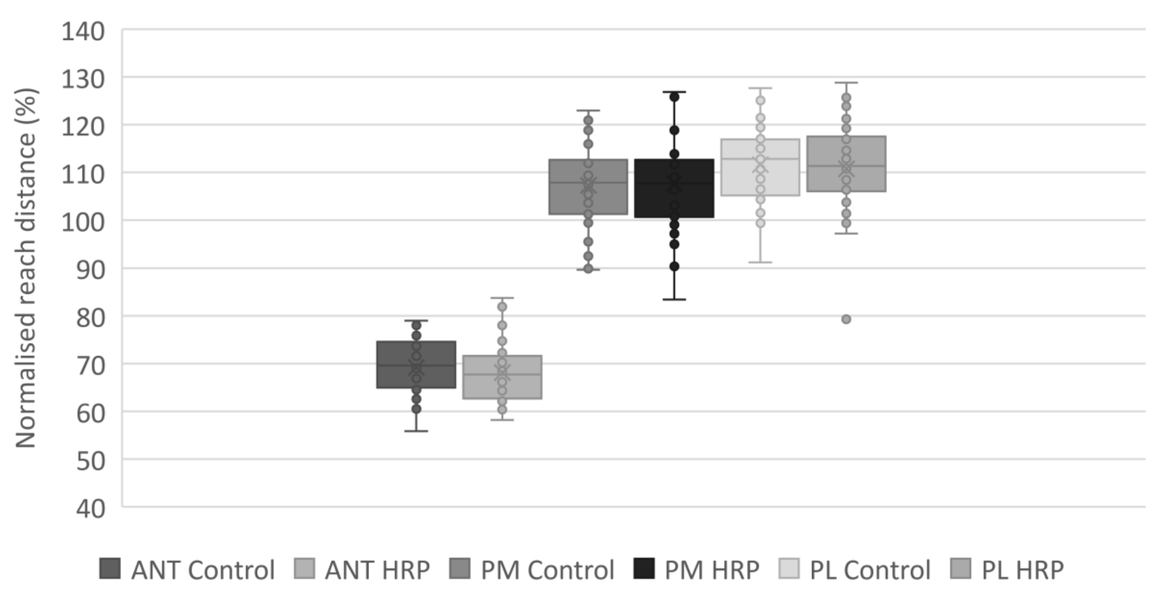


Figure 5-10: Box & Whisker Plot YBT, normalised reach distances (%), all rowers.

5.3.2.4 *Single-leg Squat*

The findings in section 5.3.1.4, meant composite score for the SL squat was not taken forward for further analysis. Table 5-12 shows the association (PEA) between a positive QASLS score during a SL squat and the likelihood of being in the HRP group.

Table 5-12: Correlation between QASLS components and HRP

		PEA (%)
Arm strategy		44
Trunk alignment		45
Pelvic plane	Loss of horizontal plane	44
	Excessive tilt or rotation	48
Thigh motion	WB thigh moves into hip adduction	42
	NWB thigh not held in neutral	40
Knee position	Noticeable valgus	45
	Signficant valgus	56
Steady stance	Touches down with NWB foot	44
	Stance leg wobbles noticeably	37

PEA; Percentage exact agreement, WB; weight bearing, NWB; non-weight bearing.

5.3.2.5 *Hip Strength*

The findings in section 5.3.1.5 allowed adduction strength and frontal plane hip strength ratios to be taken forward for further analysis. The data was visualised using box and whisker plots. No identifiable threshold was established for the complete group or for females (Figure 5-11). Area under the ROC curve analysis (AUC) showed the model quality to be poor for all rowers (AUC 0.532). When male athletes are viewed in isolation only (Figure 5-11), a ratio of 1.2 indicates a possible prognostic threshold. Results of test accuracy for male rowers are presented in Table 5-13 with ROC curves in Figure 5-12 (AUC 0.667).

Isolated hip adduction strength values showed limited association and poor test accuracy for all rowers (OR = 1.13, 95%CI -2.91 – 5.18) and male rowers (OR = 0.54, 95%CI -2.11 – 3.80).

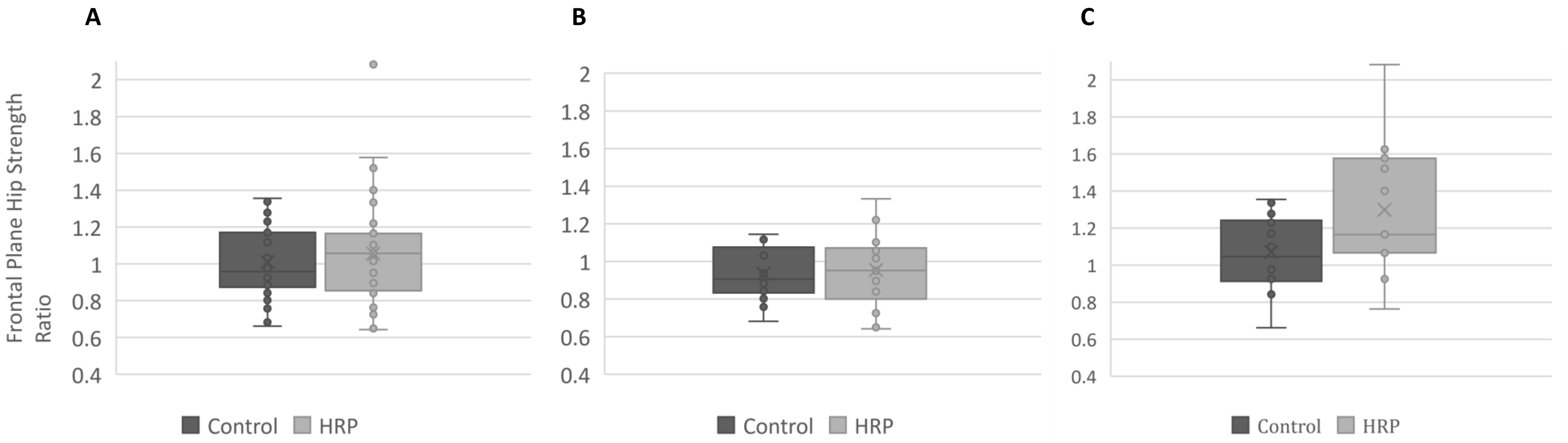


Figure 5-11: Box & Whisker Plot, isometric hip adduction/abduction strength ratios (A) all rowers, (B) females and (C) males.

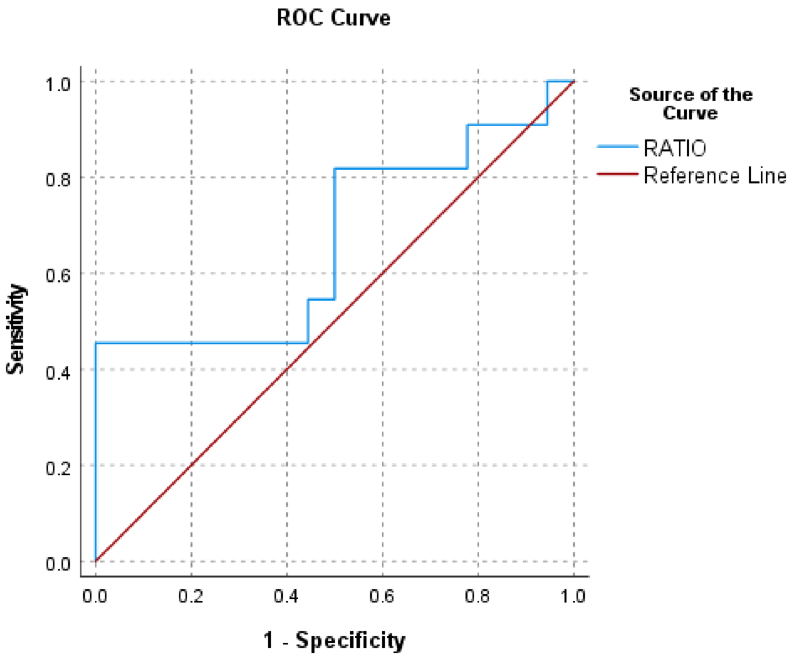


Figure 5-12: ROC curve, hip strength ratio, male participants.

Table 5-13: Frontal Plane Hip Ratio, male rowers.

Test Accuracy Outcome	**HRP**
Sensitivity	0.45
Specificity	0.72
PPV	0.50
NPV	0.68
+ve LR	1.64
-ve LR	0.76
OR	2.17 (0.45 – 10.44)

PPV, positive predictive value; NPV, negative predictive value; +ve LR, positive likelihood ratio; -ve LR, negative likelihood ratio; OR, odds ratio.

5.3.2.6 *Multivariate analysis*

Univariate analysis and suppositions for logistic regression allowed internal rotation, squat depth, and isometric hip adduction/abduction strength ratios to be taken forward for further analysis. Table 5-14 presents the results in full. Both sex and hip IR were found to have significance within the model (*p ≤0.05*).

Table 5-14: Results of multiple logistic regression investigating the association between several screening assessments and history of HRP.

	OR (95% CI)	*p*-value
Sex	**9.78 (1.84 – 52.04)**	**0.00**
Ratio	9.72 (0.41 – 229.22)	0.16
IR	**0.92 (0.85 – 0.99)**	**0.03**
Squat Depth	1.04 (0.96 – 1.13)	0.35

R^2 = 0.17 (Cox & Snell), 0.23 (Nagelkerke), Model X^2 (4) = 10.68, p = 0.03. Significant p-values are in ***bold****.*

5.4 Discussion

The primary aim of this study was to establish whether a series of physical screening tests distinguished between rowers, with and without, a history of HRP. The secondary aim was to establish if any of the variables demonstrated construct validity in identifying rowers with a history of HRP. The findings will be discussed relative to each aim and assessment.

5.4.1 IR Range of movement

This study found hip IR was reduced in elite male rowers with a history of HRP ($p < 0.01$) but not in elite female rowers. This reflects recent findings in male footballers where hip IR has been shown to be significantly decreased in football players with hip or groin time loss injuries in the previous season (Tak et al., 2016).

Hip IR correlates with cam morphology in a variety of male athletic populations including American football players (Kapron et al., 2012) and football (soccer) players (Mosler et al., 2018) and decreased IR is associated with an increased risk of developing hip pain in the presence of cam morphology (Khanna et al., 2014). Wedatilake et al., (2021) recruited male and female rowers and found a significant negative correlation between IR and cam morphology in rowers. The average IR range reported in their study was 33 ± 7° and 48 ± 10° for males and females, respectively. The differences in ROM reported reflect the differences found in this current study and may in part explain why IR was not associated with HRP in female rowers as females more commonly present with smaller cam morphology (Hetsroni et al., 2013).

Squat depth has been shown to significantly and negatively correlate with passive hip IR ROM ($r = -0.239$; $p < 0.001$) (Kim et al., 2015). The importance of this is explored in more detail in the next section (5.4.2). The findings of this section of the study suggest there is a relationship between IR and a history of HRP in the rowing population.

5.4.2 Double-leg Squat

No significant differences were found in the kinematics of a body-weight DL squat task between elite rowers with and without a history of HRP. Percentage of mean squat depth was 1.8 - 2.8% lower in the control group verses individuals with a history of HRP. The differences were comparable to those reported by Ng et al., (2015). This may be clinically relevant in the rowing population whereby the *catch* position *(see* Figure 1-2*A)*, which delineates the start of the *drive* phase of the rowing stroke, is composed of a triple extension pattern like that of a deep squat: hip flexion, knee flexion, dorsiflexion. Restriction in hip range, which may be indicated by loss of squat depth, is detrimental to both the health and performance of elite rowers. Greater angles of hip flexion at the catch are known to be important in generating large foot forces (Buckeridge et al., 2014) and contribute to increased stroke length (McGregor et al., 2007). Similarly, smaller hip flexion ranges are associated with greater lumbar-pelvic flexion angles (Buckeridge et al., 2012), which may lead to increased spinal loading and injury risk in a population with a large burden of lumbar spine injury.

Several studies (Bagwell, Snibbe, et al., 2016; Diamond et al., 2017; Lamontagne et al., 2009; Ng et al., 2015) have assessed squat mechanics in individuals with FAIS and found squat depth to be diminished when compared with controls, however these papers included symptomatic participants. The present study assessed asymptomatic rowers, none of whom reported pain or symptoms during any part of the assessment. Maximum squat depth, as a pain provocative assessment, has previously been identified as having diagnostic utility for screening those with FAIS (Reiman et al., 2015). It has also been found that squat depth achieved is similar when comparing individuals with asymptomatic cam morphology verses controls without (Ng et al., 2015). As a screening tool it may therefore lack validity in determining those with a history of HRP, as there is an absence of pain. However, nine individuals (28%) with a history of HRP were unable to squat below 60% leg length compared with only one individual (3%) of the control group. This warrants further investigation.

Previous literature investigating squat depth in HRP identified alterations in pelvic motion during a maximal depth squat. This included a reduction in sagittal pelvic range of movement at maximum depth (Ng et al., 2015), decreased posterior tilt during the descent (Bagwell, Snibbe, et al., 2016) and reduced total pelvic range of movement (Lamontagne et al., 2009). The alterations in pelvic motion are a proposed mechanism for impingement, likely due to the earlier abutment of the acetabulum with the femoral head-neck junction in the presence of cam and/or pincer morphology. Bagwell et al., (2016) found that alongside an increase in anterior pelvic tilt, there was a decrease in peak hip internal rotation and decreased hip extensor moment compared to the control group. The latter inferring decreased hip extensor muscle activity, which may explain the resultant pelvic position. A more detailed assessment of pelvic motion and the inclusion of squat kinetics may have provided further insight into the similarities seen between the participants in this study.

Trunk position was neither assessed, nor controlled for, during the DL squat which may have explained the lack of difference seen between the two cohorts. Diamond et al., (2017) also found no differences in depth when individuals with FAIS performed an unconstrained squat. A reduction in depth was found once the squat set-up limited the contribution of the trunk and pelvis, thereby isolating the hip joint motion. Restricting, and/or accounting for trunk motion, may have allowed for a more detailed understanding of hip kinematics by removing potential compensatory patterns. However, this may have reduced the external validity of the assessment.

The instructions given to the participants regarding the execution of the squat may have affected the reliability of the findings. Although participants were instructed to stand with their feet shoulder distance apart and squat to a comfortable depth, video analysis showed that execution of this instruction differed between individuals. The high standard deviation of squat depth seen in both groups (6.2 - 10.0%) reinforced the differing movement strategies adopted. As elite rowers, squatting as part of weight room training, is a fundamental part of a weekly training programme (Gee et al., 2011). Therefore, there may be ecological validity in not constraining movement strategy employed when conducting a DL squat. However, if the desired outcome is identification of hip range of movement, which is translatable to the rowing stroke, there may have been greater efficacy in controlling foot position as it is more reflective of the boat set up. Although there is some scope for adjustments to stature, width, splay, and angle of the feet in the boat, this is minimal as this is constrained by the dimensions of the foot-stretcher and the rowing hull.

Preliminary findings suggest that individuals with a history of HRP can achieve comparable squat depths to those without HRP. Although there appears to be substantial overlap between the squat depths achieved in those individuals with a history of injury verses those without. The HRP group contained more individuals who were unable to squat below 60% of their leg length. This warrants further investigation to establish whether a pre-determined cut-off value such as this, aids in distinguishing between those who are at high-risk verses low risk of injury.

5.4.3 Y-Balance Test

No differences were seen in the assessment of the YBT between rowers with and without a history of HRP when considering isolated movements or composite scores. It has been shown that performance during the YBT varies according to sport (Stiffler et al., 2015), although normal reach distances in the elite rowing population have not been previously been investigated. The reach distances reported for all groups in this study were consistently higher than those reported for in division 1 collegiate athletes in multidirectional sports such as basketball, hockey and football (Stiffler et al., 2015) but lower than those reported for younger varsity and novice aged rowers (Chimera & Kremer, 2016). As standing dynamic, postural-control is not a sport-specific requirement in rowing, the assessment may not be appropriate to detect between group differences in those who have specialised within a non-weight bearing sport, with limited exposure to transferrable balance tasks.

Previous literature has shown that the PM and PL components of a YBT are able to distinguish between individuals with HRP verses asymptomatic controls when considering pre-arthroscopic FAI (Johansson & Karlsson, 2016) and footballers with hip or groin pain (Linek et al., 2019). In both cases the symptomatic groups reported shorter reach distances. Both studies reported correlations between PM and PL reach distances and subscales of the

Copenhagen Hip and Groin Outcome Scores (Johansson & Karlsson, 2016; Linek et al., 2019). Linek et al., (2019) also found a correlation with composite scores, pain and symptoms. The present study investigated an asymptomatic group with only a history of symptoms and no individual reported pain during the assessment. As hip pain is known to negatively affect balance (Freke et al., 2018), this may explain why no signficiant differences were seen in this study.

Asymmetries in reach distance have been shown to correlate with lower limb injury risk. There were no differences in limb reach asymmetries between rowers with and without a history of HRP. Two studies (Plisky et al., 2006; Smith et al., 2015) have reported that asymmetry in anterior reach of great than 4 cm is associated with an increased risk of sustaining lower limb injury, however this measure was not normalised for limb length as is recommended (P. A. Gribble et al., 2012), therefore comparison is difficult. It has also been reported that adolescent females with composite reach scores of less than 94% limb length, are 6.5 times more likely to have a lower extremity injury (Plisky et al., 2006). The females in the present study, who had a history of HRP, had scores of 98.5% whereas males achieved reach distances around 96.4% of their standing limb length.

Hip strength is known to be correlated with YBT reach distances, with hip adduction strength deficits explaining reduction in both PM and PL reach distances (Freke et al., 2018). No differences were found in the hip strength of the rowers in this study, which may account for the similairities also seen in reach distances between groups. Only abduction and adduction strength was assessed, and no information pertaining to muscle activity was collected, therefore no firm conlcusions can be drawn here, epsecially as both external rotation (Gordon et al., 2013) and hip flexion (Freke et al., 2018) strength have also been shown to influence this assessment.

The current findings suggest there is no relationship between a history of HRP in this elite rowing population and either isolated or composite reach distances achieved in the YBT. It is possible that the test is not applicable to a cohort where dynamic postural control is challenged in a seated position, as is seen in rowing.

5.4.4 Single-leg Squat

A SL squat was assessed as it is a challenging task with the potential to amplify compensatory movements that may not be detected during a DL squat task (Malloy, Neumann, et al., 2019). It was anticipated that individuals with a history of HRP would score positively on test components, which encouraged the weight-bearing limb into a position of relative hip impingement: hip adduction, loss of pelvic alignment. The results show no relationship between rowers with, and without a history of HRP and assessment of a SL squat. Qualitative scoring showed no difference in either composite test scores or individual components of the QASLS assessment.

Previous work has shown no difference in peak hip joint adduction or internal rotation in those with HRP (Harris-Hayes et al., 2020) and 6° less peak hip adduction in those with FAIS (Malloy, Neumann, et al., 2019). Reducing excessive hip adduction during functional tasks in those with HRP is associated with reduced pain (Harris-Hayes et al., 2018). The present study investigated an asymptomatic group with a history of HRP, therefore they may have already generated positive compensatory movements, thus avoiding moving into positions of relative impingement. However, in post-surgical cases of FAIS, these deficits in SL squat performance are known to exist 1-2 years post hip arthroscopy (Charlton et al., 2016), although this may be reflective of the older cohort with more advanced pathology than was assessed in this study. There were no between group differences found in hip strength, which may provide insight as to why no differences in hip adduction/thigh motion were detected as medial knee displacement is correlated with activation of the abductors and adductors (Mauntel et al., 2013) and reduced abductor function (Crossley et al., 2011). As we didn’t use EMG, it is not possible to validate this theory.

Differences in pelvic biomechanics were anticipated in those with a history of HRP but this was not found. Greater pelvic obliquity has been seen post-operatively in those with FAIS (Charlton et al., 2016). During the similar movement pattern of stepping-down, those with FAIS demonstrate increased pelvic tilt compared with controls (Lewis, Loverro, et al., 2018). The latter findings were larger in females compared with males. Although males and females are known to use different movement strategies during a SL squat (Graci et al., 2012), no sex differences were found in any aspect of the SL squat assessment in this study. In Chapter 4, the QASLS assessment tool was shown to have excellent intrarater reliability for most test elements, except for the elements determining pelvic biomechanics which were still shown to have substantial intrarater agreement (73-84%). This concurs with other studies investigating qualitative assessment of SL squat whereby both pelvic tilt and obliquity were shown to be less reliable compared to either hip adduction or trunk flexion assessment (Barker-Davies et al., 2018). Pelvic motion has also been shown to be less reliable when compared to 3D motion analysis (Herrington & Munro, 2014) although in both instances, measures were deemed to still be at an acceptable level. Taking this into consideration, further analysis of QASLS composite scores with the exclusion of pelvic data was performed. No significant between-group differences were found.

Reductions in hip flexion, knee flexion and squat depth have been previously reported in HRP (Harris-Hayes et al., 2020), these biomechanical markers are not taken into consideration with the QASLS method. We analysed SL squat performance using sagittal views and may have gained greater insight into these variables had we also used frontal plane imaging. Although knee flexion range and squat depth are not considered using QASLS, this angle may have permitted more detailed analysis of both the trunk and pelvic positioning, therefore inferring relative hip flexion, and providing greater insight into potential biomechanical deficiencies.

Single-leg squat is routinely advocated as a useful screening tool to assess dynamic lower limb alignment and muscular control, as well as injury risk, as it is indicative of the demands required in sports-related movements (McGovern et al., 2018; Whatman, Hume, et al., 2012). It is possible that the SL squat assessment is not transferrable in rowers as lower limb loading occurs in a seated, not a standing, weight-bearing position. This may in part explain the lack of between group differences seen.

5.4.5 Hip Strength

This study is the first to report hip strength data in an elite rowing population. It was hypothesised that isometric hip adduction/abduction strength, including hip strength ratios, would be different between those with a history of hip injury and those without. The study found no significant difference in hip frontal plane strength absolute values or ratios, between previously injured and non-injured cohorts.

Differences were seen in adductor strength between the sexes, with males producing significantly greater adductor strength relative to females. Males with a history of HRP had stronger adductors than controls and demonstrated larger frontal plane hip strength ratios when compared with those with no injury history. These differences were greater than the %SEM reported in Chapter 4 but below the MDC. The difference seen in the males' strength ratio was a consequence of an increase in adductor strength.

Previous studies have identified adductor strength deficiencies as a risk factor for hip and groin injury (Ryan et al., 2014; Whittaker et al., 2015) although the majority of this literature pertains to adductor-related groin pain and other defined clinical entities of hip and groin pain (Weir et al., 2015). When specifically considering HRP, Brunner et al. (2016) found no differences in hip strength, including adductor strength, in adolescent ice hockey players with FAIS, asymptomatic FAI and controls without morphology. While Mosler et al., (2018) found an association between higher abduction strength and pincer morphology but not cam. When considering advanced FAIS, adductor strength deficits have also been reported in pre-surgical candidates (Casartelli et al., 2011; Tsai et al., 2004).

The hip adduction strength data reported for male rowers is similar to the data reported in field hockey (Beddows et al., 2020) and football (Mosler et al., 2016). Both of these studies however employed eccentric break tests, which are known to produce greater strength outputs (Bohannon, 1988), whereas this study used isometric make tests. This may infer greater strength potential in the rowing population, but the sports-specific demands on this musculature are not comparable. Muscle action during the rowing stroke is predominantly concentric in action, with the muscles of the hip contributing to extension of the joint and stabilization of the pelvis during the *drive* phase (Hosea & Hannafin, 2012). Several papers have investigated muscle activity of the hip extensors during the rowing stroke, specifically: gluteus maximus (Pollock et al., 2009), biceps femoris (Nowicky et al., 2005; Pollock et al., 2009; Turpin et al., 2011) and semitendinosus (Turpin et al., 2011). The posterior head of adductor magnus is known to be a primary hip extensor (Neumann, 2010) but their role in rowing has not previously been investigated. The adductor magnus is known to be a more effective hip extensor than either the hamstring or gluteus maximus when the hip is in flexion as the moment arm changes with increasing hip angle (Neumann, 2010). This may explain the large isometric adductor strength numbers seen in the male rowers relative to other sports although this does not account for the sex differences seen.

Pooled data for all rowers showed isometric abduction and adduction strength as 2.4 ± 0.5 Nm/kg and 2.5 ± 0.6 Nm/kg, respectively. When males were analysed in isolation, these figures increased to 2.4 ± 0.4 and 2.7 ± 0.5 Nm/kg, which were higher than figures previously reported in football (abduction 2.0 ± 0.4, ADD 1.8 ± 0.6) (Thorborg et al., 2014). Our methodology involved athlete stabilisation, whereas Thorborg et al., (2014) did not. This may partly explain the higher values seen, as lack of stabilisation results in a reduced ability to produce force (Krause et al., 2007). In the same study, Thorborg et al., (2014) reported no difference in isometric strength measures in the injured leg of footballers with adductor-related groin pain but did find eccentric adductor strength deficits. Hip/groin issues in rowers are typically classified as hip joint-related pain such as FAIS and ALT (Thornton et al., 2017), whereas much of the literature has been conducted in multidirectional sports (Ryan et al., 2014; Whittaker et al., 2015). Unlike rowing, these sports have high eccentric adductor requirements for running, kicking and change of direction and hip-groin pain injuries are accounted for by a variety of clinical entities and not just hip-joint related pain. The lack of homogeneity in sport demands in conjunction with the variation in injuries sustained, reinforces the notion that injury risk profiles are likely to differ between sports and generalisation of research findings are not possible.

The average frontal plane strength ratios in the present male rowing cohort was 1.1 ± 0.3, not including rowers with a history of hip issues. These values were similar to those reported in previous studies for field hockey, 1.1 ± 0.2 (Beddows et al., 2020) and football, 1.2 ± 0.2 (Mosler et al., 2016). The differences between those with and without hip injury history were not found to be signficiant which is in agreement with previous literature which has shown no relationship between time loss hip injuries and strength profiles in football (Mosler et al., 2016). During the rowing stroke, high, unopposed hip adductor forces may lead to replication of impingement positions equivalent to those elicited in the FADDIR impingement test, resulting in high shear and compression forces across the anterior hip-joint structures. This may in part explain the differences reported between athletic cohorts. As a retrospective review, there is no clear causal relationship to these findings. The differences found may have contributed to injury or may be a consequence of rehabilitation and/or adaptation following injury.

5.4.6 Construct validity

5.4.6.1 *Association between injury history and ROM*

Lower hip IR ROM was associated with historical hip-related injuries in rowers. ROM of less than 30° provided good specificity for identifying rowers with injury history (SP 0.88) although this was not supported by other clinical prediction rules. However, in the male cohort, a positive test using a threshold of 30° showed a good association between those with and without previous HRP (SN 0.67; SP 0.84; PPV 0.73; NPV 0.80; OR 10.67, 95% CI: 1.91 – 59.62) with fair discriminatory ability (AUC 0.756). This is in line with previous literature which has shown decreased IR in 90° flexion is associated with history of TL injuries in other male athletic populations (Tak et al., 2016). These findings suggest that IR ROM is a potential mechanism for screening to determine injury history. This should be interpreted with caution due to the wide confidence interval reported which may reflect the small sample size.

5.4.6.2 *Association between injury history and deep squat*

Using a threshold of 60%, a positive test, i.e., inability to squat below 60% LL, showed a strong association between those identified as having a history of HRP (SN 0.27; PPV 0.09; +ve LR 8.73; OR 11.63, 95% CI: 8.87 - 14.38) but a negative test did not demonstrate the same association (SP 0.97; NPV 0.56; -ve LR 0.72). Although sensitivity is poor, high specificity was found, indicating a lower type 1 error rate. Although an association is present, these were poor at discriminating those with and without a history of HRP (AUC 0.60). These findings suggest DL squat depth may have some validity in screening to determine injury history due to HRP.

5.4.6.3 *Association between injury history and YBT and single-leg squat.*

YBT and SL squat assessments were not found to be valid in determining whether rowers had a history of HRP. No association was found between any of the YBT test directions, or between the components of a SL squat using a dichotomous qualitative scoring system and history of HRP. The latter showed agreement between 37 – 56%, which is no better than chance.

5.4.6.4 *Association between injury history and isometric hip adduction/abduction strength*

Isolated frontal plane strength had poor association with historical hip-related injuries in rowers. Isometric hip adduction/abduction strength ratios were also poor at distinguishing between female rowers with and without a history of HRP. In males, hip strength ratios ≥1.2 demonstrated good specificity for identifying rowers with injury history (SP 0.72) and fair discriminatory accuracy (AUC 0.667) however this was not supported by other clinical prediction rules. Average limb strength data was used in this study. Pilot data for this thesis found no difference in isometric hip adduction/abduction strength between dominant verses non-dominant values in healthy rowers and no association between limb dominance and side of the boat in sweep oar rowing (bow side verses stroke side; see Appendix 10.8).

5.4.6.5 *Relationship between multivariate screening and injury history*

When applying the model to all rowers, 17-23% of variance in the HRP group was explained by the screening. The percentage of classification accuracy increased from 50.0% pre-application of the model to 66.1% post-application. This was significant ($p = 0.03$). The model showed sex as an important, confounding variable ($p = 0.08$) with the OR for having a history of HRP being 9.78 times higher in females. However, the wide supporting confidence intervals reflect a high level of uncertainty around the true association.

Of the remaining variables, only hip IR was also shown to have significance in the model. Every 1° decrease in hip IR range was associated with an 8% increase in the odds of having a history of HRP. This aligns with previous findings of Tak et al., (2016) who found football players with a previous history of hip or groin time-loss injuries had reduced hip IR. Although hip strength reported a large OR, the vast confidence interval suggests the true probability of this contributing to the model is low (du Prel et al., 2009).

5.4.7 General Discussion

5.4.7.1 *Sex-differences*

In this study, males and females displayed differing findings in several of the screening tests when considering both univariate and multivariate analysis. This is not the first study to identify that sex is a potential effect modifier in those with hip-related groin pain following the work of Lewis et al., (2018a; 2018b) and King et al., (2019). Both groups found sex-specific differences in lower-limb biomechanics in individuals with HRP during both low and high impact activities.

There are many factors which may account for the differences seen between males and females. A key factor in this cohort may be the known anatomical and morphological variances seen between the groups. A cross-sectional observational study on 20 asymptomatic elite rowers (8 females, 12 males), demonstrated a degree of cam morphology, with a difference in mean alpha angle between the groups (males 75.9°; females 64.7°) (Wedatilake et al., 2021). In the general population, there is a higher prevalence of cam morphology reported in asymptomatic males compared with females (13.0 to 72.0% to 0.0 to 11.7%, respectively), the sex difference is not seen when considering pincer morphology (van Klij et al., 2018). Females tend to have smaller alpha angles (and therefore smaller size of cam morphology), increased acetabular version, and increased femoral anteversion (Hetsroni et al., 2013). These factors are hypothesised to contribute to differences in lower limb kinematics between the sexes however, as discussed in Chapter 2.3, literature to date does not support that bony morphology in isolation leads the development of HRP such as FAIS. As such, radiological assessment was not included in this study therefore the proposed role that anatomical variation plays in this study cannot be verified.

Sex-specific biomechanical differences are known to exist in healthy cohorts during SL squatting and landing tasks (Lephart et al., 2002; Weeks et al., 2015) as well as during an ergometer based rowing stroke (McGregor et al., 2008). Male rowers not only generate significantly greater peak forces when rowing, but also demonstrate significantly less anterior pelvic rotation during the stroke compared with females (McGregor et al., 2008). These variables are likely to contribute to differences in loading around the hip joint.

Analysis of sex-specific groups may have led to the groups being under powered due to a reduction in the sample size. This may explain why in some instances, no between group differences were seen due to the likelihood of a type II error. As this study has included a specialised set of participants in national rowing team, this is unavoidable.

Sex-differences are an important consideration, as analysis of mixed cohorts may invalidate any potential association between injury and profiling measures. As such, consideration of sex as an effect modifier should be taken forwards. Equally, findings from one cohort should not be directly transposed onto the other as it cannot be assumed that screening variances for one group apply to the other.

5.4.7.2 *Previous Injury*

The rowers involved in this study all trained at the national training centre. Consequently, following a period of HRP, all would have had access to rehabilitation in an enhanced-care setting. It is known that lower limb biomechanics are positively improved following a period of hip strengthening and muscle pattern re-training (Harris-Hayes et al., 2018), which may explain the small number of differences seen in this study. Short-term measures of conservative management for FAIS have shown favourable outcomes in pain and function up to 6 months post-intervention (Mallets et al., 2019), however there is limited evidence of investigation into longer term outcomes of rehabilitation following HRP. It is therefore unknown if improvements plateau or change with increasing time. The time point between assessment and previous HRP episode was not standardised, therefore differences between the groups may have been diluted due to differing stages of recovery. Previous hip/groin injuries are known to be associated with increased injury risk (Mosler, Weir, et al., 2018). However, it is hypothesised that risk of recurrence diminishes with increasing time from injury due to accumulation of chronic training loads (Grindem et al., 2016; Stares et al., 2018). It is possible that in an elite cohort, physical and biomechanical characteristics could change with increasing duration from previous injury episode due to ongoing manipulation and individualisation of training regimes. The impact of this on the findings of this study are unclear.

The present study identifies some physical qualities and biomechanical variables which warrant further investigation. Although these assessments infer some differences between those with and without a history of HRP, it is unknown whether differences were a cause or a consequence of the event.

5.5 Conclusion

This is the first known study to investigate the relationship between history of HRP in elite rowers and a battery of physical screening assessments. Differences were found in passive hip IR ROM in males but not in females. Both sexes tended to have shallower squat depths compared with rowers with no injury history, but no differences were seen in single-leg tasks and strength measures. Although no clear differences were seen in hip strength measures, adductor strength and frontal plane strength ratios tended to be higher in males with a history of HRP.

Construct validity was shown when discrete thresholds were used for IR, in males only, and when interaction of assessments was investigated. Sex appears to be an important factor in identifying rowers with a history of HRP and should be taken into consideration when planning the next stages of screening development.

5.6 Summary

To develop a screening protocol, risk factors need to be prudently chosen based on evidence and thorough reasoning (Bullock et al., 2021). The aim of Chapter 5 was to identify and validate risk factors for HRP relative to the rowing population. Prior to conducting a prospective cohort study, a retrospective analysis was conducted to establish the relationship between history of HRP and a series of physical screening assessments.

Although there was sizeable overlap between the squat depths achieved between elite male rowers with and without a history of HRP, the group with previous HRP contained more individuals who were unable to squat below 60% of their leg length. This warrants further investigation due to the comparable nature of a squat and the rowing stroke. Significant between group differences were seen for IR ROM but this was only found in male rowers. No differences were seen in males or females for strength metrics, Y-balance assessment, or SL squat. It is possible that these latter assessments are not transferrable to rowing, where athletes have limited exposure to standing balance tasks.

Evaluation of construct validity suggests that historical HRP is associated with squat depth in all rowers, and with IR in males. These findings should be interpreted with caution as isolated assessments do not reflect the complex interaction of variables associated with injury (Bittencourt et al., 2016). It is also unclear whether differences, or lack of, in assessment data from athletes with historical HRP is a result of previous injury or subsequent injury management.

Development of a screening model based on single-variable assessment risks the exclusion of factors, which in the presence of an appropriately controlled confounding variable, may show significance (Sun et al., 1996). Multivariate analysis revealed that prediction accuracy in the detection of historical HRP was strongly influenced by sex, with the probability of having a history of HRP being higher in females. This enhances the suggestion that morphology in isolation, is not responsible for HRP, and specifically FAIS. Both the prevalence of FAIS and size of respective morphology is higher in males (Hetsroni et al., 2013; van Klij et al., 2018), yet more females in this cohort than males presented with a history of HRP. As a result, the role of sex as an effect modifier should be explored further.

The findings of this retrospective analysis revealed that the following physical assessments and characteristics showed an association with previous HRP in elite rowers:

- Hip IR
- DL squat
- Isometric hip adduction/abduction strength
- Sex

These assessments will therefore be taken forwards into the next study to prospectively investigate the associations between potential risk factors and the development of HRP.

CHAPTER 6

6 INTRINSIC RISK FACTORS FOR HIP-RELATED PAIN IN ELITE ROWERS: A PROSPECTIVE STUDY

Chapter 5 investigated the association between physical screening assessments and previous hip-related pain (HRP) in elite rowers. This identified a series of potential risk factors for HRP in an elite rowing population.

In the quest to develop a screening protocol, a prospective cohort study is required to identify associations between potential risk factors and injury (Finch, 2006). This is a necessary precursor to the validation of a screening tool (Bahr, 2016; Kent et al., 2020).

6.1 Introduction

Hip-related pain (HRP) is a term used to describe a series of non-arthritic hip-joint conditions experienced by young and middle-aged active adults, often presenting with hip and/or groin pain (M. G. King et al., 2019; Weir et al., 2015). HRP is the most common cause of long-standing hip and/or groin pain among sporting populations (Rankin et al., 2015) and the second most common cause of lower limb musculoskeletal pain (J. Kemp et al., 2019). In rowing, HRP is poorly reported compared to the prevalence of low back pain (LBP), accounting for only 2.8 to 8.4% of total injuries seen (Smoljanovic et al., 2009; Trease et al., 2020). However, the incidence appears to be increasing in recent years, with a prevalance of 14-15% and 0.7 episodes per 1000 training days seen across a recent Olympic cycle (*data from Great Britain Rowing Team injury surveillance, 2021*).

Hip-related pain can be sub-classified into (1) femoroacetabular impingement syndrome (FAIS), (2) acetabular dysplasia and or hip instability and (3) other conditions without distinct osseous morphology (Reiman et al., 2020). Recent studies in rowers have reported a high prevalance of cam morphology (Wedatilake et al., 2021), labral tears (Bittersohl et al., 2019;

Boykin et al., 2013; Wedatilake et al., 2021) and cartilage degeneration (Bittersohl et al., 2019), albeit often in asymptomatic cohorts (Bittersohl et al., 2019; Wedatilake et al., 2021).

Identification of risk factors for injury is an important component of injury prevention research (Finch, 2006; van Mechelen et al., 1992). A risk factor is an exposure associated with the onset of a problem (Riley et al., 2013). These can be person specific (intrinsic) or environmental specific (extrinsic) (Bullock et al., 2021; Meeuwisse et al., 2007). These factors typically inform screening protocols used to detect individuals at risk, and consequently implement strategies to mitigate these risks (Bahr, 2016). To the authors knowledge, there are no studies that have been conducted looking at risk factors for hip-related injuries in rowers. Risk factors for hip and/or groin pain in other sports, such as previous injury and low adductor strength, are widely reported, with conflicting findings for hip range of motion (Mosler, Weir, et al., 2018; Ryan et al., 2014; Whittaker et al., 2015). These studies reported a variety of definitions for hip and/or groin pain beyond the taxonomy of hip-related pain.

The true prevalence of HRP in sport is known to be underreported due to the traditional time-loss definitions used in epidemiological studies which may only capture a small proportion of problems (Bahr et al., 2020; Esteve et al., 2015). HRP is often insidious and chronic, and often symptoms are transient in nature, therefore it is common for athletes to continue to train and compete in its presence (Esteve et al., 2015; Philippon et al., 2007). Therefore, to identify risk factors associated with the true burden of HRP, individuals who seek medical attention without time-loss should also be considered (Clarsen et al., 2013).

As identified in the previous chapter, sex-differences are an important consideration with screening assessments demonstrating between-sex differences for Y-balance reach distances and strength measures. Similarly, sex-differences have been found when assessing lower-limb biomechanics in those with HRP (M. King et al., 2019; Lewis, Khuu, et al., 2018; Lewis, Loverro, et al., 2018). Further understanding of how factors are influenced by sex can help optimise injury management and prevention strategies. As such, sex will be considered as an effect modifier during analysis as failure to do so may invalidate any potential association between injury and profiling measures.

6.1.1 Aims

The primary aim of this exploratory chapter is to describe the associations between a series of lower limb screening tests and the development of HRP in elite rowers. It is hypothesised that rowers who develop HRP will demonstrate reductions in hip range of motion, squat depth and differences in isometric hip adduction/abduction strength when compared those who don’t develop HRP.

A secondary aim is to establish whether screening assessments are effective at identifying individuals at-risk of developing HRP. To capture the complete burden of HRP in elite rowing, these questions will be considered with respect to all HRP issues irrespective of time-loss, as well as for isolated TL-injuries.

6.1.2 Objectives

The objectives will relate to the following risk factors:

- Passive hip internal rotation.
- Double Leg (DL) squat depth.
- Isometric hip adduction/abduction strength: absolute measures and strength ratios.

The objectives of this chapter are to ascertain the differences in a) screening characteristics (risk factors) between rowers who do and don’t go on to develop HRP; b) screening characteristics between rowers who do and don’t go on to develop TL-injuries due to HRP and c) screening characteristics between males and females.

The second half of the chapter will look to ascertain a) the association between risk factors and the development of HRP in elite rowers and b) the association between risk factors and the development of TL-injuries due to HRP.

The final objective is to explore the potential of risk factors to determine the development of HRP. Full cohort (all rowers) and sub-groups for sex will be considered for each objective.

6.2 Methodology

6.2.1 Study Participants

Across the study period, fifty-eight rowers were eligible as they were based at the National Squad training centre, on the centralised training programme, for six months following screening assessment. Seventy-four percent of the cohort was categorised as Tier 5: World Class rowing participants, as per the classifcation framework proposed by McKay et al., (2021). The remainder were classed as elite/international (Tier 4 = 26%). Sex, age, stature, and mass baseline characteristics were recorded for all participants.

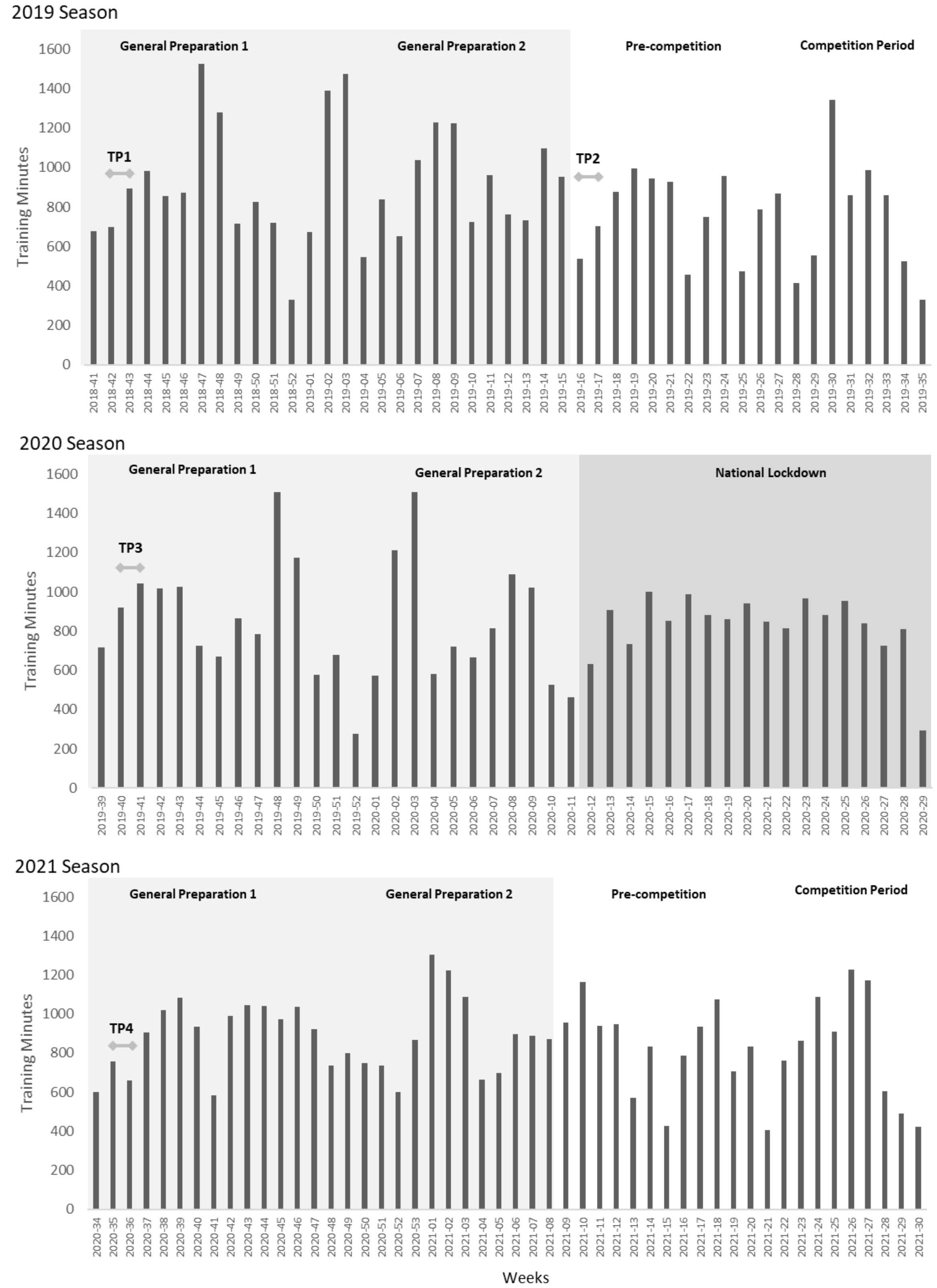
Participants were excluded if they were experiencing, or had signficant history of, any lower limb or back injury, or had any medical condition, which may affect the outcome of the assessment. This was established through face-to-face interviewing. Following the application of eligibility criteria, three rowers were excluded resulting in fifty-five participants. See Table 6-1 for participant characteristics and groups.

At their first screening session, each individual was supplied with a participant information sheet (see Appendix 10.2) and written informed consent was obtained (see Appendix 10.3). The study received ethical approval from the University of Salford Reasearch ethics committee (ref: HSR1819-049).

6.2.2 Study Design

Screening data was collected from all senior rowers based at the Great Britain Rowing Team elite training centre as part of routine screening practices. Assessments were completed every six-months: at the start, and midway through the season. Data was collected over two and a half seasons (October 2018 to October 2020; see Figure 6-1). Data collection was paused in March 2020 due to Covid-19 leading to a 12 month gap between assessments (see COVID-19 IMPACT STATEMENT). The late inclusion of hip internal rotation (IR) as an assessment coupled with the impact of Covid-19 resulted in gaps in IR data for the male athletes due to differences in routine screening practices between the sexes.

Figure 6-1: GBRT Training Programme overview, including training phases and screening time-points



⟷ ***TP,** time-point of data collection (screening); **General Preparation 1 & 2**: Approximately 70% of the annual training programme is performed during the general preparation phases. This typically includes high volumes of low-intensity, sports-specific training. **Pre-competition & competition period:** Approximately 30% of the annual training programme is performed with a reduction in training volume, an increase in higher intensity training and more competition-specific training.*

In recent years, there has been an emergence of research investigating the association between training load and injury (Gabbett, 2020). It is acknowledged that this an important extrinsic injury risk consideration which would benefit from further exploration. However, as training intensity distribution and training time are viewed as necessary contributors to performance (Fiskerstrand & Seiler, 2004; Mikulic, 2011), it is not the intention of this research to explore this question with this cohort. As all participants were members of the national rowing squad, completing the national training programme, training load will be assumed to be a constant factor.

6.2.3 Musculoskeletal Screening Procedure

Each participant underwent four assessments: 1) passive internal hip rotation, 2) double-leg squat, 3) isometric hip abduction and 4) isometric hip adduction strength as part of their routine screening. The methods are described fully in the General Methods Chapter 3.

6.2.4 Injury Classification

To capture the complete burden of HRP in elite rowing, two separate injury classifications were used.

6.2.4.1 *Hip-related pain group*

Participants were classified into two groups:

1. *Hip-related pain group*: those presenting with any HRP-symptoms.
2. *Control group*: those without HRP-symptoms

HRP was defined according to the ‘Consensus recommendations on the classification, definition and diagnostic criteria of hip-related pain in young and middle-aged active adults from the International Hip-related Pain Research Network, Zurich 2018’ (Reiman et al., 2020).

Sub classification of HRP was not possible as radiology was not routinely conducted. This is a key requirement in the diagnostic triage for FAIS (Griffin et al., 2016). Those presenting with other classifications of hip and/or groin pain, as per the Doha agreement (Figure 1-5) (Weir et al., 2015), were excluded from the study.

6.2.4.2 *Time-loss HRP*

The HRP group was further classified using the following injury definitions as recommended by Clarsen et al., (2013):

1. Medical attention (MA): Injury resulting in medical attention, but no time loss from sports participation, training and/or competition.
2. Time loss (TL): Injury resulting in time loss from training ± competition.

The following time loss categories was used as recommended by Bahr et al. (2020): 1-7 days, 8-28 days, >28days.

Participants were grouped by the medical staff and injury history was validated using the athlete medical records, which are stored in the English Institute of Sports (EIS) Performance Data Management System (PDMS). Consent was not only obtained from the individual athletes involved (see Appendix 10.3) but organisational agreement was also sought from the EIS and British Rowing National Governing Body (see *appendix 10.4 and 10.5*) to access this information.

Time loss from training was cross-referenced with an in-house injury surveillance system to clarify the exact period affected. In cases where participants had a history of bilateral HRP, the most symptomatic and/or functionally restricting limb, as identified by the participant, was used for analysis.

6.2.5 Data Analysis

Statistical analysis was conducted in SPSS (version 26, IBM Corporation, New York, USA). Each data collection time point was analysed independently.

6.2.5.1 *Between group comparisons: HRP/TL-HRP group verses Control group*

Analysis was carried out to establish differences in risk factor profiles (dependent variables; hip IR, squat depth, isometric hip adduction/abduction strength) in relation to the study groups (independent variables: control group verses HRP or TL-HRP groups). Therefore, two separate analyses were conducted comparing: those experiencing HRP verses those not experiencing HRP, and those experiencing TL-injuries due to HRP with those not experiencing HRP. The latter being a sub-group of those with HRP. Individuals who had received MA were excluded as this meant the individual had received medical support which precluded them from being in the non-TL control group.

Data was assessed for normality using a Shapiro-Wilk test prior to any further analysis. Means and standard deviations were used to summarise each risk factor. Linear regression was used to calculate mean differences, 95% confidence intervals and levels of significance with a *p*-value set at <0.05. Sex has previously been identified as an effect modifier in HRP (M. King et al., 2019; Lewis, Khuu, et al., 2018; Lewis, Loverro, et al., 2018), so a covariate for sex was included in all analysis. Males and females were also analysed in isolation by fitting a separate linear regression analysis to each sex.

Additional linear regression was conducted to evaluate the differences in variables (hip IR, squat depth, isometric hip adduction/abduction strength) between males and females.

6.2.5.2 *Risk factor Associations: Univariate Analysis*

Binary logistic regression was conducted to determine which risk factors (independent variables) were associated with the development of (1) HRP or (2) TL-injury due to HRP (outcomes). Odds ratios, 95% confidence intervals and levels of significance (*p* <0.05) were reported.

6.2.5.3 *Predictive ability*

Previous literature is unable to clearly delineate thresholds to assess predictive ability of hip IR range of motion (ROM) or squat depth. This is due to the heterogenous populations, which frequently involve symptomatic individuals at the time of assessment in conjunction with the variations in methodological approach. As such, an exploratory analysis was conducted to ascertain the predictive performance of risk factors in identifying individuals who may go on to develop HRP. This was only conducted on factors that were shown to have an association.

Receiver operating characteristic (ROC) curves were used, plotting sensitivity against 1 – specificity, using continuous data sets to determine an optimal cut-off threshold with the best risk performance (D. G. Altman & J. M. Bland, 1994; Nahm, 2022). The area under the curve (AUC) was then calculated to measure the overall test accuracy, with values > 0.5 being required to determine a meaningful test, preferably > 0.8 to be deemed acceptable (Nahm, 2022). This process was conducted using SPSS software.

Where ROC curves are unable to identify an appropriate cut-off threshold, data visualisation using box and whisker plots were utilised to identify thresholds. Following this, clinical prediction rules were applied as described in section 5.2.4.2. It is known that sensitivity and specificity are inversely related, therefore, a conservative threshold was adopted to produce high levels of specificity (Bahr, 2016). This can be a powerful measure in elite sport where time constraints are high and primary prevention strategies can be at odds with performance.

6.3 Results

During the study period, fifty-five rowers participated equating to 138 participant seasons. Full participant characteristics are presented in Table 6-1. Twenty-seven rowers experienced HRP during the study period. Fourteen rowers (male = 5) experienced TL-HRP injuries during this time accounting for 97 training days. Average TL was 5 days (±4). The distribution of time loss injuries are reported in Table 6-1 as per the IOC recommendatons (Bahr et al., 2020). There were no signficant differences in participant characteristics for those experiencing HRP (± TL-injuries) verses controls (*p* > 0.5).

Table 6-1: Participant baseline characteristics stratified by time loss duration.

Eligible Participants	**All participants**	**HRP participants, TL durations (days)**			
		0 (n = 13)	**1-7 (n = 9)**	**8 – 28 (n = 5)**	**>28 (n = 0)**
Age (years) mean ± SD	26 ± 3	26 ± 3	26 ± 3	26 ± 2	-
Sex (M, %)	28 (51%)	5 (36%)	2 (20%)	2 (40%)	-
Body mass (kg) mean ± SD	83.6 ± 11.6	84.3 ± 13.2	87.4 ± 12.5	87.4 ± 7.0	-
Stature (cm) mean ± SD	185.6 ± 8.5	184.8 ± 9.9	187.9 ± 9.0	187.9 ± 6.6	-

S.D, standard deviation; 95% CI, 95% confidence intervals; TL, time loss duration, days; M, male; kgs, kilograms; cm, centimetres

6.3.1 Between group comparison: HRP verses Controls

In this cohort of elite rowers, after adjusting for sex as a confounding factor, there were no between group differences for any of the strength outcomes. The IR for those with HRP was on average lower (MD: -2.4° to -7.8°) than the control group, and the mean squat depth was higher (MD: 3.9% to 5.2%). The differences were often statistically significant. In the settings in which the p>0.05, there was still a large amount of evidence to support both claims. Full results are reported in Table 6-2. The same findings were seen when males and females were analysed in isolation (Table 6-3) however when considering squat depth, the size of the mean difference was larger between the male cohorts than the female ones.

Table 6-2: Results of linear regression analysis for all rowers: HRP verses Controls

		Control		**HRP**			
		Mean	**S.D.**	**Mean**	**S.D.**	**Mean Difference (95% CI)**	***p*-value**
IR (°)	TP1	41.2	8.4	36.5	10.1	**-7.8 (-12.7, -2.9)**	**0.03**
	TP2	43.7	10.0	41.1	7.6	**-5.9 (-11.8, 0.0)**	**0.05**
	TP3	38.9	6.7	38.2	8.5	-2.4 (-6.5, 1.7)	0.25
	TP4*	-	-	-	-	-	-
SQUAT DEPTH (%LL)	TP1	49.1	8.7	52.4	6.9	4.5 (-9.3, 0.5)	0.07
	TP2	49.7	5.6	53.6	8	3.9 (-0.4, 8.1)	0.07
	TP3	50.7	5.8	55.5	7.5	**4.7 (0.5, 8.9)**	**0.03**
	TP4	47.4	7.1	54.6	9.5	**5.2 (0.03, 10.4)**	**0.05**
ABDUCTION (NM/KG)	TP1	2.44	0.32	2.34	0.42	-0.10 (-0.36, 0.16)	0.45
	TP2	2.52	0.30	2.51	0.36	-0.06 (-0.27, 0.15)	0.60
	TP3	2.35	0.38	2.36	0.39	0.28 (-0.20, 0.26)	0.52
	TP4	2.48	0.74	2.57	0.61	0.09 (0.33, 0.52)	0.66
ADDUCTION (NM/KG)	TP1	2.58	0.50	2.33	0.57	-0.11 (-0.42, 0.21)	0.50
	TP2	2.78	0.48	2.76	0.58	0.12 (-0.16, 0.39)	0.41
	TP3	2.40	0.73	2.35	0.53	0.08 (-0.26, 0.42)	0.64
	TP4	2.55	0.44	2.78	0.82	0.22 (0.24, 0.67)	0.34
RATIO	TP1	1.07	0.23	1.01	0.26	0.13 (-0.14, 0.16)	0.86
	TP2	1.11	0.18	1.12	0.27	**0.10 (0.00, 0.20)**	**0.05**
	TP3	1.02	0.25	1.01	0.23	0.04 (-0.09, 0.16)	0.55
	TP4	1.08	0.18	1.08	0.17	0.03 (-0.09, 0.15)	0.60

HRP, hip-related pain; S.D, standard deviation; 95% CI, 95% confidence intervals; TP; time-point of data collection; IR, internal rotation (°); %LL, percentage of leg length; Nm/kg, newton-meters per kilogram; Significant mean differences and p-values are in ***bold****. *hip IR data not collected at this time point due to the impact of Covid-19.*

Table 6-3: Results of linear regression analysis for male / female rowers: HRP verses Controls

		Males						***Females***					
		Control		**HRP**				**Control**		**HRP**			
		Mean	**S.D.**	**Mean**	**S.D.**	**MD (95% CI)**	***p*-value**	**Mean**	**S.D.**	**Mean**	**S.D.**	**MD (95% CI)**	***p*-value**
IR (°)	TP1	37.2	5.7	29.0	9.1	-8.3 (-15.1, -1.5)	0.19	48.0	8.4	40.8	8.1	-7.3 (-14.9, 0.51)	0.07
	TP2$^{\theta}$	-	-	-	-	-	-	47.7	7.8	41.8	7.3	-6.0 (-12.3, 0.5)	0.06
	TP3	36.6	5.0	33.3	8.1	-3.4 (-9.0, 2.4)	0.23	42.0	7.7	40.5	7.8	-1.6 (-9.1, 6.1)	0.60
	TP4*	-	-	-	-	-	-	-	-	-	-	-	-
SQUAT DEPTH (%LL)	TP1	50.7	8.0	55.5	7.7	4.9 (-2.5, 12.1)	0.20	46.7	9.7	50.8	6.2	4.1 (-2.8, 11.0)	0.23
	TP2	49.6	5.9	53.5	9.3	3.9 (-2.7, 10.5)	0.24	49.8	5.6	53.7	7.5	3.9 (-12.0, 9.8)	0.19
	TP3	50.0	5.9	56.1	7.3	**6.1 (0.3, 11.9)**	**0.05**	51.7	6.0	55.3	7.8	3.6 (-0.3, 14.1)	0.25
	TP4	47.4	7.1	53.7	10.1	6.3 (-2.0, 14.6)	0.83	50.7	5.2	55.0	9.5	4.4 (-2.9, 11.5)	0.22
ABDUCTION (NM/KG)	TP1	2.39	0.32	2.43	0.3	0.04 (-0.25, 0.33)	0.77	2.52	0.32	2.31	0.47	-0.22 (-0.62, 0.20)	0.93
	TP2	2.52	0.36	3.2	0.72	0.12 (0.20, 1.16)	0.10	2.52	0.35	2.62	0.32	0.09 (-0.18, 0.38)	0.53
	TP3	2.47	0.30	2.26	0.3	-0.2 (-0.48, 0.06)	0.17	2.20	0.40	2.41	0.43	0.21 (-0.54, 0.12)	0.21
	TP4	2.48	0.74	2.09	0.51	-0.39 (-1.06, 0.28)	0.77	2.22	0.33	2.82	0.51	**0.6 (-1.00, -0.10)**	**0.02**
ADDUCTION (NM/KG)	TP1	2.74	0.53	2.78	0.39	0.04 (-0.40, 0.49)	0.80	2.34	0.34	2.10	0.51	-0.25 (-0.68, 0.20)	0.28
	TP2	3.08	0.25	2.26	0.35	-0.26 (-1.10, 0.54)	0.64	2.45	0.36	2.56	0.37	0.11 (-0.20, 0.42)	0.47
	TP3	2.65	0.80	2.74	0.54	0.09 (-0.60, 0.75)	0.87	2.08	0.51	2.16	0.41	0.07 (-0.38, 0.54)	0.69
	TP4	2.55	0.44	2.16	0.49	-0.39 (-0.85, 0.07)	0.24	2.23	0.36	3.08	0.79	**0.86 (0.26, 1.44)**	**0.02**
RATIO	TP1	1.15	0.25	1.19	0.27	0.04 (-0.20, 0.28)	0.86	0.94	0.11	0.93	0.21	-0.01 (-0.19, 0.17)	0.26
	TP2	1.23	0.15	1.46	0.23	**0.23 (0.07, 0.39)**	**0.02**	0.98	0.10	0.98	0.13	0.01 (-0.10, 0.10)	0.88
	TP3	1.08	0.34	1.22	0.25	0.18 (-0.14, 0.42)	0.27	0.95	0.14	0.90	0.12	-0.05 (-0.18, 0.08)	0.37
	TP4	1.07	0.18	1.05	0.18	-0.02 (-0.20, 0.16)	0.10	1.01	0.13	1.09	0.17	0.08 (-0.06, 0.22)	0.31

HRP, hip-related pain; S.D, standard deviation; 95% CI, 95% confidence intervals; MD, mean difference; TP; time-point of data collection; IR, internal rotation (°); %LL, percentage of leg length; Nm/kg, newton-meters per kilogram; Significant mean differences and p-values are in ***bold.*** **hip IR data not collected at this time point due to the impact of Covid-19.* $^{\theta}$ *the late inclusion of hip internal rotation as an assessment resulted in gaps in the IR data for the male athletes due to differences in routine screening practices between the sexes.*

6.3.2 Between group comparison: Time Loss HRP injuries verses Controls

After adjusting for sex as a confounding factor, there were no between group differences for any of the strength outcomes. Mean differences for those in the TL-HRP group tended to be lower for IR (-3.9° to -10.2°) and higher for squat depth (2.9 to 5.9%) compared with the control group. Although this was not always statistically significant for IR and squat depth, the direction of difference was consistent across all time-points. Full results are reported in Table 6-4. Male rowers experiencing TL-injures tended to have reduced IR, reduced squat depths and higher adduction:abduction strength ratios. Female rowers experiencing TL-injuries had lower IR range (p < 0.03) and shallower squat depths, but the latter was not statistically significant. Full results for males and females are presented below (Table 6-5).

Table 6-4: Results of linear regression analysis for all rowers: TL-HRP verses Controls

		Control		TL-HRP			
		Mean	S.D.	Mean	S.D.	Mean Difference (95% CI)	*p*-value
IR (°)	TP1	41.2	8.4	36.5	10.1	**-8.2 (-13.9, -2.4)**	**0.01**
	TP2	43.7	10.0	37.5	3.8	**-10.2 (-16.4, 4.0)**	**0.01**
	TP3	38.9	6.7	35.8	7.2	-3.9 (-8.5, 0.8)	0.10
	TP4*	-	-	-	-	-	-
SQUAT DEPTH (%LL)	TP1	49.1	8.7	53.4	6.9	4.5 (-1.6, 10.6)	0.14
	TP2	49.7	5.6	52.7	7.8	2.9 (-2.0, 7.7)	0.24
	TP3	50.7	5.8	57.2	8.8	**5.9 (0.8, 11.1)**	**0.03**
	TP4	47.4	7.1	54.7	11.1	4.6 (-1.1, 11.8)	0.10
ABDUCTION (NM/KG)	TP1	2.44	0.32	2.34	0.42	-0.09 (-0.34, 0.16)	0.47
	TP2	2.52	0.30	2.33	0.32	-0.23 (-0.47, 0.01)	0.06
	TP3	2.35	0.38	2.25	0.37	-0.07 (-0.34, 0.20)	0.59
	TP4	2.48	0.74	2.41	0.34	0.04 (-0.45, 0.53)	0.88
ADDUCTION (NM/KG)	TP1	2.58	0.50	2.33	0.57	-0.01 (-0.37, 0.34)	0.94
	TP2	2.78	0.48	2.69	0.41	0.03 (-0.24, 0.30)	0.84
	TP3	2.40	0.73	2.35	0.52	0.04 (-0.40, 0.47)	0.86
	TP4	2.55	0.44	2.74	0.51	0.31 (-0.09, 0.72)	0.12
RATIO	TP1	1.07	0.23	1.01	0.26	0.05 (-0.13, 0.22)	0.59
	TP2	1.11	0.18	1.19	0.29	**0.17 (-0.46, -0.23)**	**0.01**
	TP3	1.02	0.25	1.06	0.26	0.07 (-0.10, 0.24)	0.41
	TP4	1.08	0.18	1.14	0.15	0.10 (-0.05, 0.24)	0.18

TL-HRP, time-loss hip-related pain; S.D, 95% CI, 95% confidence intervals; standard deviation; TP; time-point of data collection; IR, internal rotation (°); %LL, percentage of leg length; Nm/kg, newton-meters per kilogram; Significant mean differences and p-values are in ***bold.*** **hip IR data not collected at this time point due to the impact of Covid-19.*

Table 6-5: Results of linear regression analysis for male / female rowers: TL-HRP verses Controls

		Males						***Females***					
		Control		**TL-HRP**				**Control**		**TL-HRP**			
		Mean	**S.D.**	**Mean**	**S.D.**	**MD (95% CI)**	***p*-value**	**Mean**	**S.D.**	**Mean**	**S.D.**	**MD (95% CI)**	***p*-value**
IR (°)	TP1	37.3	5.66	30.2	12	-7.1 (-16.0, 1.8)	0.11	48	8.4	38.7	5.8	**-9.3 (-0.19, 0.47)**	**0.03**
	TP2$^{\theta}$	-	-	-	-	-	-	47.7	7.8	37.5	3.8	**-10.2 (-17.7, -3.72)**	**0.004**
	TP3	36.6	5.0	34.8	9.9	-1.8 (-8.8, 5.2)	0.59	42	7.7	36.5	5.7	-5.5 (-12.3, 1.3)	0.10
	TP4*	-	-	-	-	-	-	-	-	-	-	-	-
SQUAT DEPTH (%LL)	TP1	50.7	8.01	54.3	8.3	3.6 (-5.6, 12.8)	0.42	46.7	9.7	52.1	5.3	5.4 (-5.3, 16.1)	0.22
	TP2	49.6	5.9	51.8	10.3	**2.2 (-5.7, 10.1)**	**<0.001**	49.8	5.6	53.2	6.7	3.4 (-3.0, 9.8)	0.27
	TP3	50.0	5.9	54.9	8.9	4.8 (-2.4, 12.2)	0.26	51.7	6	58.6	9	6.9 (-0.3, 14.1)	0.08
	TP4	47.4	7.1	50.5	9.8	6.3 (-6.5, 12.7)	0.70	50.7	5.2	58.1	11.9	7.4 (-0.1, 0.2)	0.12
ABDUCTION (NM/KG)	TP1	2.39	0.32	2.41	0.27	0.03 (-0.31, 0.35)	0.89	2.52	0.32	2.34	0.3	-0.19 (-0.59, 0.23)	2.81
	TP2	2.52	0.25	2.06	0.29	-0.46 (-0.75, -0.17)	0.59	2.52	0.35	2.43	0.28	-0.1 (-0.27, 0.41)	0.52
	TP3	2.47	0.30	2.23	0.30	-0.23 (-0.57, 0.09)	0.24	2.2	0.4	2.27	0.44	0.06 (-0.48, 0.44)	0.75
	TP4	2.48	0.74	2.29	0.4	0.39 (-0.65, 12.7)	0.65	2.22	0.33	2.5	0.3	-0.28 (0.13, 1.25)	0.18
ADDUCTION (NM/KG)	TP1	2.74	0.53	2.95	0.37	0.21 (-0.32, 0.74)	0.44	2.34	0.34	2.11	0.45	-0.23 (-0.59, 0.23)	2.91
	TP2	3.08	0.36	3.03	0.43	**-0.05 (-0.47, 0.37)**	**<0.001**	2.45	0.36	2.52	0.29	0.08 (-0.27, 0.41)	0.64
	TP3	2.65	0.80	2.76	0.37	0.11 (-0.68, 0.90)	0.35	2.08	0.51	2.06	0.39	-0.02 (-0.48, 0.44)	0.92
	TP4	2.55	0.44	2.52	0.29	-0.39 (-0.54, 0.48)	0.65	2.23	0.36	2.92	0.61	**0.69 (0.13, 1.25)**	**0.04**
RATIO	TP1	1.15	0.25	1.29	0.25	0.14 (-0.19, 0.47)	0.37	0.94	0.11	0.91	0.2	-0.03 (-0.23, 0.17)	0.73
	TP2	1.23	0.15	1.58	0.20	**0.35 (0.17, 0.53)**	**<0.001**	0.98	0.1	1.05	0.12	0.07 (-0.04, 0.18)	0.22
	TP3	1.08	0.34	1.26	0.26	0.18 (-0.17, 0.53)	0.09	0.95	0.14	0.92	0.15	-0.03 (-0.17, 0.11)	0.70
	TP4	1.07	0.18	1.11	0.12	0.02 (-0.25, 0.17)	0.90	1.01	0.13	1.17	0.18	0.16 (0.13, 1.25)	0.13

TL-HRP, time loss hip-related pain; S.D, standard deviation; 95% CI, 95% confidence intervals; TP; time-point of data collection; IR, internal rotation (°); %LL, percentage of leg length; Nm/kg, newton-meters per kilogram; Significant mean differences and p-values are in ***bold****. *hip IR data not collected at this time point due to the impact of Covid-19.* $^{\theta}$ *the late inclusion of hip internal rotation as an assessment resulted in gaps in the IR data for the male athletes due to differences in routine screening practices between the sexes.*

6.3.3 Sex differences: comparison of females with males

Full results for between sex differences are reported in Table 6-6. A significant difference was seen for IR, hip adduction strength and adduction:abduction strength ratios between males and females. Males presented with smaller IR ranges and larger adduction strength and adduction:abduction strength ratios (*p* <0.01). There were no differences for squat depth and hip abduction strength between males and females.

Table 6-6: Results of linear regression analysis for between-sex analysis

		Mean Difference (95% CI)	*p*-value
IR (°)	TP1	**11.3 (6.4, 16.2)**	**< 0.001**
	TP2	**12.2 (4.2, 20.0)**	**0.004**
	TP3	**6.2 (2.1, 10.4)**	**0.004**
	TP4*	-	-
SQUAT DEPTH (%LL)	TP1	-4.4 (-9.3, 0.5)	0.08
	TP2	0.2 (-4.0, 4.5)	0.92
	TP3	0.4 (-3.8, 4.6)	0.65
	TP4	2.4 (-2.8, 7.6)	0.37
ABDUCTION (NM/KG)	TP1	0 (-0.26, 0.26)	1.00
	TP2	0.19 (-0.03, 0.40)	0.09
	TP3	-0.08 (-0.31, -0.16)	0.52
	TP4	0.27 (-0.15, 0.69)	0.20
ADDUCTION (NM/KG)	TP1	**-0.55 (-0.86, -0.24)**	**<0.001**
	TP2	**-0.64 (-0.92, -0.36)**	**<0.001**
	TP3	**-0.58 (-0.92, -0.23)**	**0.002**
	TP4	0.35 (-0.11, 0.80)	0.13
RATIO	TP1	**-0.24 (-0.39, -0.09)**	**0.003**
	TP2	**-0.37 (-0.47, 0.27)**	**<0.001**
	TP3	**-0.22 (-0.35, -0.10)**	**<0.001**
	TP4	-0.01 (-0.12, 0.11)	0.93

S.D, standard deviation; TP; time-point of data collection; 95% CI, 95% confidence intervals; IR, internal rotation (°); %LL, percentage of leg length; Nm/kg, newton-meters per kilogram; Significant mean differences and p-values are in ***bold.*** **hip IR data not collected at this time point due to the impact of Covid-19.*

6.3.4 Risk Factor Associations: HRP verses Controls

Binary logistic regression, with sex included as a confounding variable, demonstrated that IR and squat depth were significant predictors of experiencing HRP injuries in elite rowers (*p* ≤ 0.05). Every 1° increase in hip IR range was associated with an 8 to 14% decrease in the odds of having HRP. Except for data collection point 2 (TP2), a 1% increase in squat height was associated with an 8 to 9% increase in the odds of having HRP. There was insufficient evidence to confirm an association between strength risk factors and likelihood of developing HRP. See Table 6-7.

Table 6-7: Risk factor associations for all rowers with HRP.

		OR (95% CI)	***p*-value**
IR (°)	TP1	**0.88 (0.81 -0.96)**	**0.00**
	TP2	**0.86 (0.76 - 0.98)**	**0.02**
	TP3	**0.92 (0.85 - 1.00)**	**0.05**
	TP4*	-	-
SQUAT DEPTH (%LL)	TP1	**1.09 (1.00 - 1.19)**	**0.05**
	TP2	1.10 (0.99 - 1.16)	0.08
	TP3	**1.09 (1.00 - 1.19)**	**0.04**
	TP4	**1.08 (1.00 - 1.16)**	**0.05**
ABDUCTION (NM/KG)	TP1	0.46 (0.07 - 3.01)	0.42
	TP2	0.29 (0.05 - 1.89)	0.20
	TP3	0.57 (0.13 - 2.38)	0.43
	TP4	1.18 (0.39 - 3.56)	0.76
ADDUCTION (NM/KG)	TP1	0.74 (0.20 - 2.81)	0.66
	TP2	1.63 (0.41 - 6.47)	0.48
	TP3	1.09 (0.41 - 2.94)	0.86
	TP4	2.03 (0.61 - 6.76)	0.25
RATIO	TP1	1.89 (0.12 -29.92)	0.65
	TP2	4.01 (0.31 – 53.49)	0.02
	TP3	4.21 (0.31 - 53.49)	0.28
	TP4	5.81 (0.01 - 258.90)	0.36

OR, odds ratio; 95% CI, 95% confidence intervals; TP; time-point of data collection IR, internal rotation (°); %LL, percentage of leg length; Nm/kg, newton-meters per kilogram; Significant associations and p-values are in ***bold****. *hip IR data not collected at this time point due to the impact of Covid-19.*

Analysis of males and females in isolation also found IR to be a significant predictor of presenting with HRP although the same was not seen for squat depth. Overall, strength factors were not shown to be predictors of HRP (Table 6-8). Although some data-collection points showed favourable *p*-values, the wide supporting confidence intervals reflect a high level of uncertainty around the true association.

Table 6-8: Risk factor associations for male & female rowers with HRP.

		Males		***Females***	
		OR (95% CI)	***p*-value**	**OR (95% CI)**	***p*-value**
IR (°)	TP1	**0.89 (0.79 - 0.10)**	**0.04**	**0.88 (0.77 - 1.00)**	**0.04**
	TP2[e]	-	-	**0.86 (0.76 - 0.98)**	**0.02**
	TP3	0.94 (0.83 - 1.06)	0.28	0.91 (0.82 - 1.02)	0.10
	TP4*	-	-	-	-
SQUAT DEPTH (%LL)	TP1	1.08 (0.96 - 1.21)	0.18	1.10 (0.97 - 1.26)	0.15
	TP2	1.06 (0.96 - 1.17)	0.27	1.09 (0.96 - 1.24)	0.17
	TP3	1.13 (0.40 - 1.29)	0.06	1.06 (0.94 - 1.18)	0.34
	TP4	1.08 (0.97 - 1.21)	0.16	1.08 (0.97 - 1.19)	0.16
ABDUCTION (NM/KG)	TP1	1.52 (0.08 - 27.37)	0.78	0.17 (0.01 - 3.00)	0.23
	TP2	**0.02 (0 - 1.06)**	**0.05**	1.31 (0.12 - 14.6)	0.83
	TP3	0.10 (0.01 - 1.57)	0.10	1.39 (0.21 - 9.00)	0.73
	TP4	0.41 (0.09 - 1.83)	0.24	**145.13 (1.18 - 17863)**	**0.04**
ADDUCTION (NM/KG)	TP1	1.75 (0.27 - 11.14)	0.56	0.24 (0.02 - 2.44)	0.23
	TP2	1.31 (0.24 - 7.20)	0.76	2.40 (0.25 - 23.45)	0.45
	TP3	1.27 (0.38 - 4.18)	0.70	0.78 (0.13 - 4.70)	0.79
	TP4	0.25 (0.03 - 1.88)	0.18	**69.93 (1.19 - 4068)**	**0.04**
RATIO	TP1	3.41 (0.11 - 110.62)	0.49	0.65 (0.01 - 65.76)	0.86
	TP2	**2585.7 (2.31-2899269)**	**0.03**	6.84 (0.01 - 4057.1)	0.56
	TP3	8.90 (0.46 - 173.55)	0.15	0.14 (0 - 55.92)	0.52
	TP4	1.09 (0.01 - 166.78)	0.97	48.77 (0.13 - 18287)	0.20

OR, odds ratio; 95% CI, 95% confidence intervals; TP; time-point of data collection IR, internal rotation (°); %LL, percentage of leg length; Nm/kg, newton-meters per kilogram; Significant associations and p-values are in ***bold****. *hip IR data not collected at this time point due to the impact of Covid-19. [e] the late inclusion of hip internal rotation as an assessment resulted in gaps in the IR data for the male athletes due to differences in routine screening practices between the sexes.*

6.3.5 Risk Factor Associations: TL-HRP verses Controls

Regression analysis including sex as a confounding variable, demonstrated that IR was the only significant predictors of TL-HRP injuries in elite rowers (*p* ≤ 0.05). Every 1° decrease in hip IR range was associated with a 12 to 14% increase in the odds of having HRP. No association was seen between any of the other risk factors and the future development of a TL injury due to HRP.

Table 6-9: Risk factor associations for all rowers with TL-HRP.

		OR (95% CI)	***p*-value**
IR (°)	TP1	**0.86 (0.76 - 0.97)**	**0.02**
	TP2[e]	-	**-**
	TP3	**0.88 (0.79 - 0.99)**	**0.04**
	TP4*	-	-
SQUAT DEPTH (%LL)	TP1	1.09 (0.97 - 1.22)	0.14
	TP2	1.07 (0.96 - 1.20)	0.22
	TP3	1.09 (0.69 - 13.35)	0.11
	TP4	1.10 (0.98 - 1.24)	0.11
ABDUCTION (NM/KG)	TP1	0.36 (0.03 - 4.96)	0.44
	TP2	0.07 (0.004 - 1.22)	0.07
	TP3	0.30 (0.04 - 2.20)	0.22
	TP4	2.53 (0.49 - 13.20)	0.27
ADDUCTION (NM/KG)	TP1	0.93 (0.17 - 5.21)	0.93
	TP2	1.29 (0.14 - 12.38)	0.82
	TP3	0.91 (0.27 - 3.10)	0.88
	TP4	4.86 (0.60 - 40.01)	0.14
RATIO	TP1	3.423 (0.06 - 199.9)	0.55
	TP2	**5.362 (0.178 – 161.913)**	**0.02**
	TP3	4.45 (0.20 - 97.60)	0.34
	TP4	58.88 (0.17 - 20698)	0.17

OR, odds ratio; 95% CI, 95% confidence intervals; TP; time-point of data collection IR, internal rotation (°); %LL, percentage of leg length; Nm/kg, newton-meters per kilogram; Significant associations and p-values are in ***bold****. *hip IR data not collected at this time point due to the impact of Covid-19. [e] the late inclusion of hip internal rotation as an assessment resulted in gaps in the IR data for the male athletes due to differences in routine screening practices between the sexes.*

Analysis of males and females in isolation found no association between predictor variables and the development of TL-HRP. Full results are presented in Table 6-9 and Table 6-10.

Table 6-10: Risk factor associations for male and female rowers with TL-HRP.

		Males		***Females***	
		OR (95% CI)	***p*-value**	**OR (95% CI)**	***p*-value**
IR (°)	TP1	0.88 (0.74 - 1.04)	0.13	0.83 (0.69 - 1.01)	0.06
	TP2[e]	-	-	0.65 (0.42 - 1.02)	0.06
	TP3	0.95 (0.81 - 1.12)	0.57	0.84 (0.70 - 1.01)	0.06
	TP4*	-	-	-	-
SQUAT DEPTH (%LL)	TP1	1.07 (0.92 - 1.24)	0.40	1.11 (0.94 - 1.32)	0.23
	TP2	1.05 (0.90 - 1.22)	0.54	1.11 (0.92 - 1.34)	0.27
	TP3	1.11 (0.95 - 1.30)	0.19	1.12 (0.95 - 1.32)	0.18
	TP4	1.06 (0.90 - 1.26)	0.47	1.14 (0.96 - 1.35)	0.15
ABDUCTION (NM/KG)	TP1	1.36 (0.03 - 74.97)	0.88	0.11 (0.002 - 5.29)	0.26
	TP2	0 (0 - 4.22)	0.09	0.33 (0.01 - 8.18)	0.50
	TP3	0.07 (0.001 - 3.88)	0.20	0.96 (0.08 - 11.94)	0.98
	TP4	0.61 (0.09 - 4.33)	0.62	25.97 (0.19 - 3469)	0.19
ADDUCTION (NM/KG)	TP1	2.95 (0.22 - 40.13)	0.42	0.17 (0.01 - 4.21)	0.28
	TP2	0.69 (0.03 - 18.32)	0.82	2.25 (0.10 - 53.76)	0.62
	TP3	1.25 (0.29 - 5.36)	0.77	0.66 (0.07 - 5.89)	0.71
	TP4	0.81 (0.05 - 14.99)	0.89	128.05 (0.34 - 47792)	0.11
RATIO	TP1	13.84 (0.06 - 3322.20)	0.35	0.26 (0 - 320.79)	0.71
	TP2	1595424 (0.02 - 1.587e+14)	0.13	432.09 (0.03 - 6759141)	0.22
	TP3	7.95 (0.24 - 266.47)	0.25	0.31 (0 - 365.41)	0.74
	TP4	4.9 (0.003 - 7510)	0.67	1628 (0.07 -40404043)	0.15

OR, odds ratio; 95% CI, 95% confidence intervals; TP; time-point of data collection IR, internal rotation (°); %LL, percentage of leg length; Nm/kg, newton-meters per kilogram; Significant associations and p-values are in ***bold****. *hip IR data not collected at this time point due to the impact of Covid-19. [e] the late inclusion of hip internal rotation as an assessment resulted in gaps in the IR data for the male athletes due to differences in routine screening practices between the sexes.*

6.3.6 Predictive ability

6.3.6.1 *ROC Curve and AUC analysis*

ROC analysis was unable to consistently define an optimal cut-off threshold for any of the risk factors by graphically demonstrating a high sensitivity plotted against 1-specificity (see examples in Figure 6-2, Figure 6-3, Figure 6-4 and Figure 6-5). AUC analysis results for test accuracy are reported in Table 6-11 for HRP and Table 6-12 for TL-HRP. Frontal plane isometric strength derivates showed no discrimination. IR and squat depth showed poor to excellent and poor to acceptable discriminatory ability respectively. Larger participant numbers would be required to support or refute the hypothesis in this instance.

Table 6-11: Findings from AUC analysis for HRP

		ALL	**MALE**	**FEMALE**
IR (°)	TP1	0.65	**0.80**	**0.77**
	TP2^{e}	0.63	**-**	**0.79**
	TP3	0.60	0.66	0.69
	TP4*	-	-	-
SQUAT DEPTH (%LL)	TP1	0.57	0.66	0.57
	TP2	0.64	0.59	0.67
	TP3	0.64	**0.71**	0.55
	TP4	**0.70**	0.66	**0.71**
ABDUCTION (NM/KG)	TP1	0.56	0.44	0.66
	TP2	0.55	**0.83**	0.46
	TP3	0.44	0.53	0.51
	TP4	0.56	0.67	0.46
ADDUCTION (NM/KG)	TP1	0.64	0.37	**0.86**
	TP2	0.41	0.56	0.33
	TP3	0.44	0.53	0.51
	TP4	0.46	0.63	0.42
RATIO	TP1	0.44	0.58	0.44
	TP2	0.49	**0.83**	0.54
	TP3	0.51	0.68	0.45
	TP4	0.59	0.47	0.69

*TP; time-pint of data collection IR, internal rotation (°); %LL, percentage of leg length; Nm/kg, newton-meters per kilogram. *hip IR data not collected at this time point due to the impact of Covid-19. ^{e} the late inclusion of hip internal rotation as an assessment resulted in gaps in the IR data for the male athletes due to differences in routine screening practices between the sexes.*

Table 6-12: Findings from AUC analysis for TL-HRP

		ALL	MALE	FEMALE
IR (°)	TP1	0.59	0.62	0.64
	TP2^{e}	0.67	-	**0.76**
	TP3	0.60	0.54	0.67
	TP4*	-	-	-
SQUAT DEPTH (%LL)	TP1	0.55	0.55	0.57
	TP2	0.53	0.51	0.52
	TP3	0.62	0.59	0.54
	TP4	0.61	0.55	0.67
ABDUCTION (NM/KG)	TP1	0.54	0.62	0.56
	TP2	0.65	**0.83**	0.64
	TP3	0.57	0.62	0.54
	TP4	0.50	0.43	0.45
ADDUCTION (NM/KG)	TP1	0.51	0.50	0.44
	TP2	0.48	0.44	0.53
	TP3	0.53	0.62	0.45
	TP4	0.57	0.58	**0.58**
RATIO	TP1	0.50	0.64	0.44
	TP2	0.58	**0.81**	0.65
	TP3	0.56	0.64	0.52
	TP4	0.64	0.54	0.68

*TP; time-point of data collection IR, internal rotation (°); %LL, percentage of leg length; Nm/kg, newton-meters per kilogram. *hip IR data not collected at this time point due to the impact of Covid-19. ^{e} the late inclusion of hip internal rotation as an assessment resulted in gaps in the IR data for the male athletes due to differences in routine screening practices between the sexes.*

6.3.6.2 *Clinical Utility: HRP*

ROC curve analysis was unable to identify clear thresholds for further analysis of IR and Squat depth. Following visual inspection (see examples in Figure 6-2, Figure 6-3, Figure 6-4 and Figure 6-5) the following thresholds were used for an exploratory analysis:

- IR ≤30°
- Squat Depth ≥60% LL

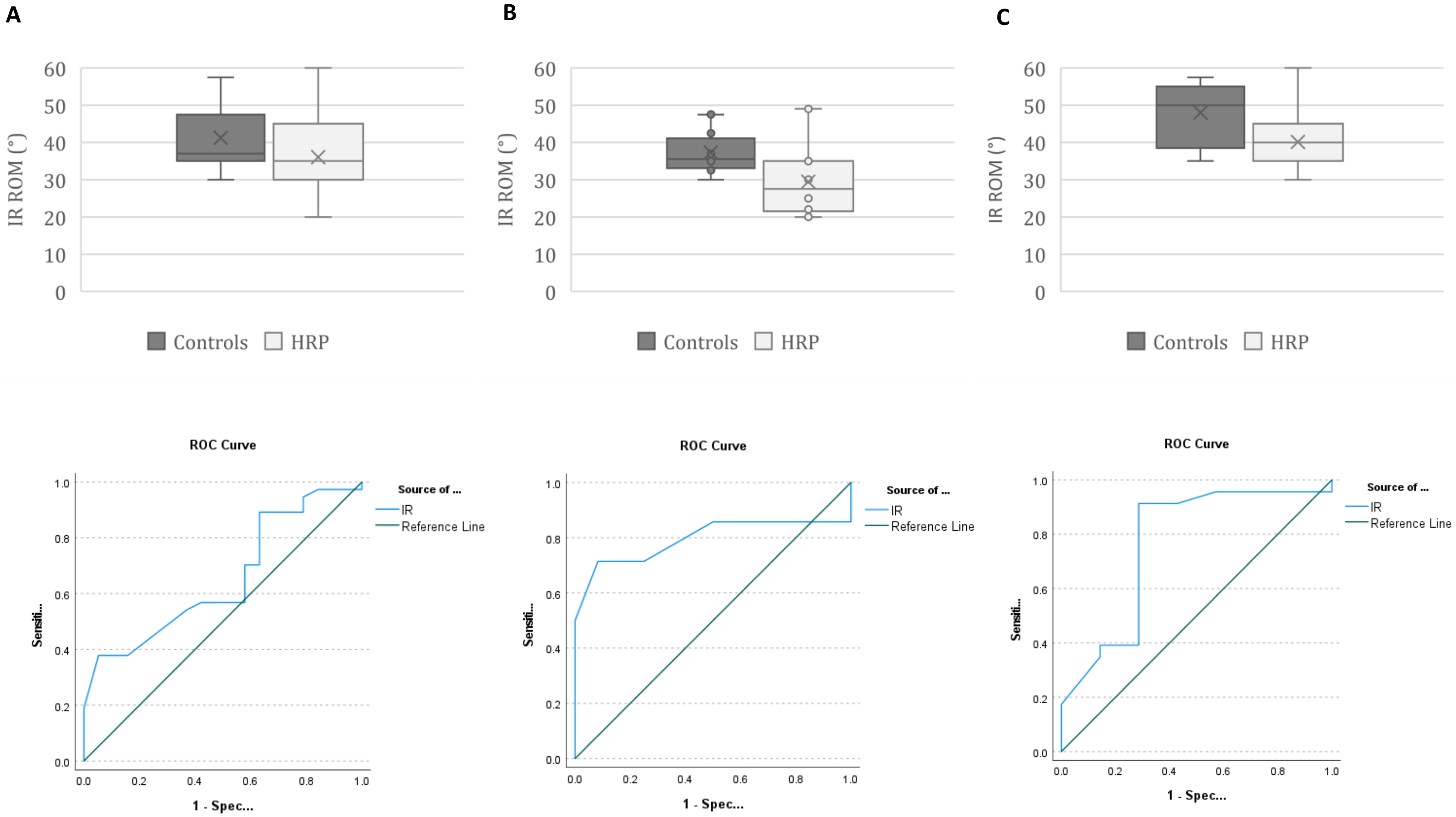


Figure 6-2: Box & whisker plots and corresponding ROC Curves for Hip IR ROM take from data collection time point 1. (A) All rowers, (B) Males and (C) Females

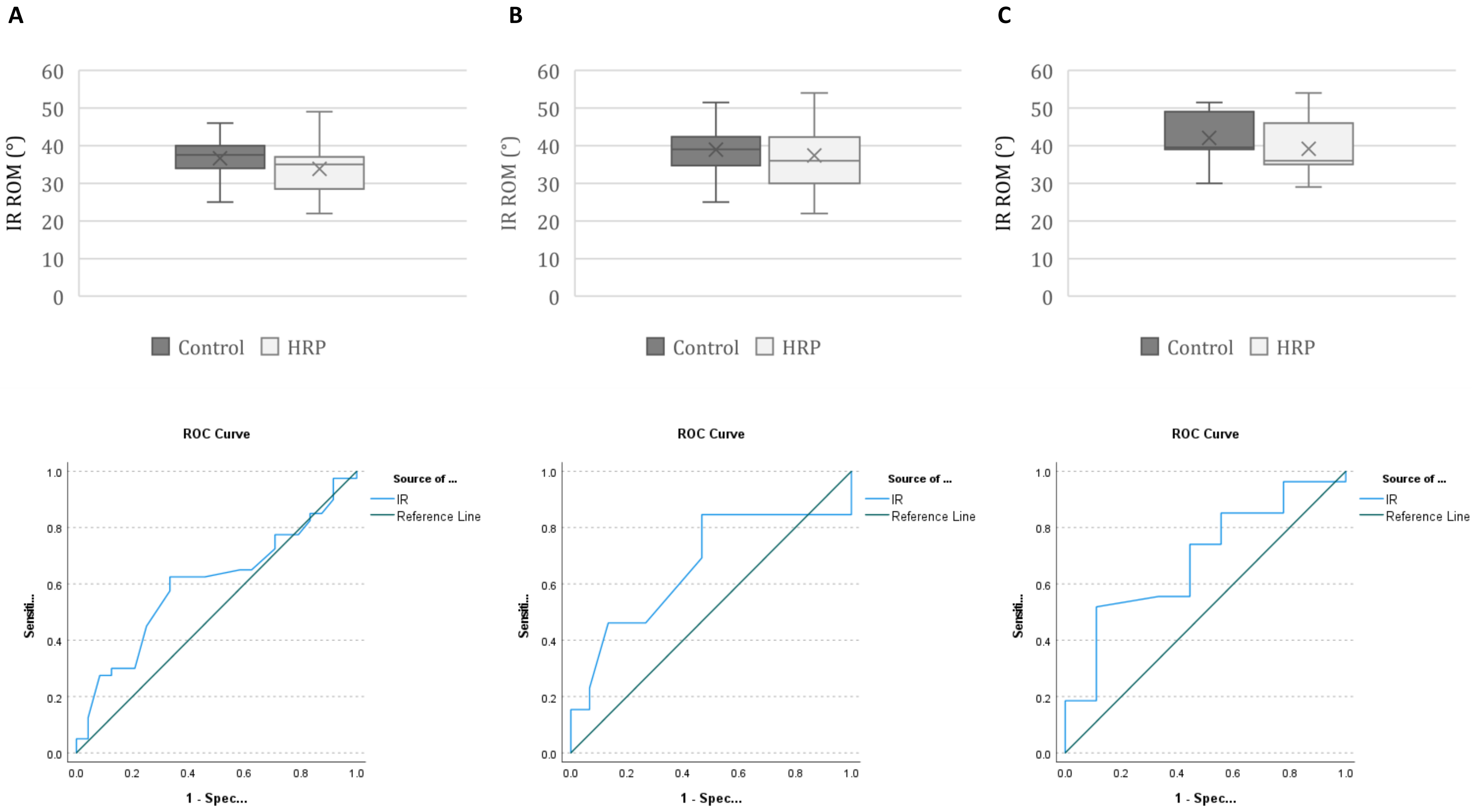


Figure 6-3: Box & whisker plots and corresponding ROC Curves for Hip IR ROM taken from data collection time point 3. (A) All rowers, (B) Males and (C) Females

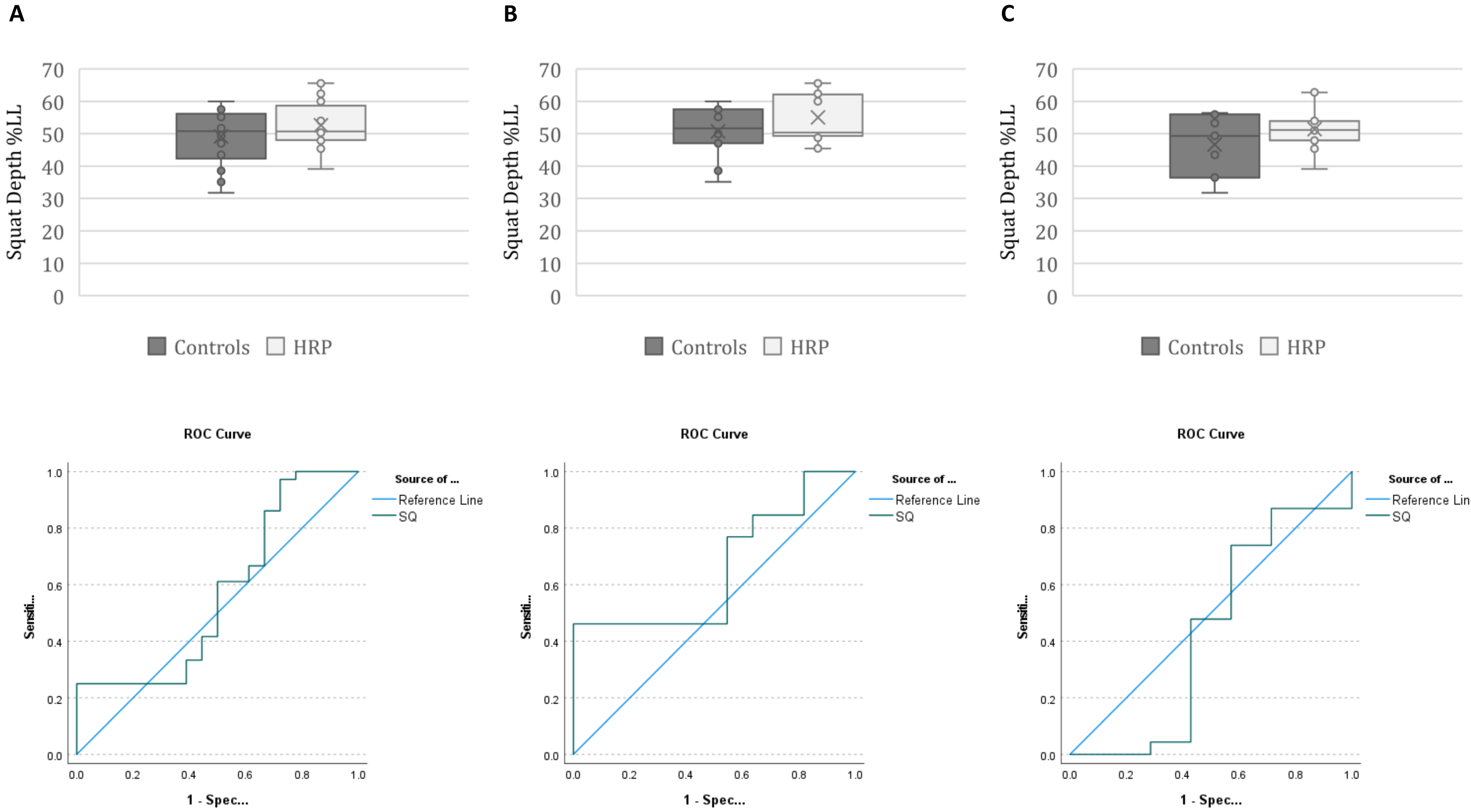


Figure 6-4: Box & whisker plots and corresponding ROC Curves for Squat Depth (%LL, leg length) taken from data collection time point 1. (A) All rowers, (B) Males and (C) Females

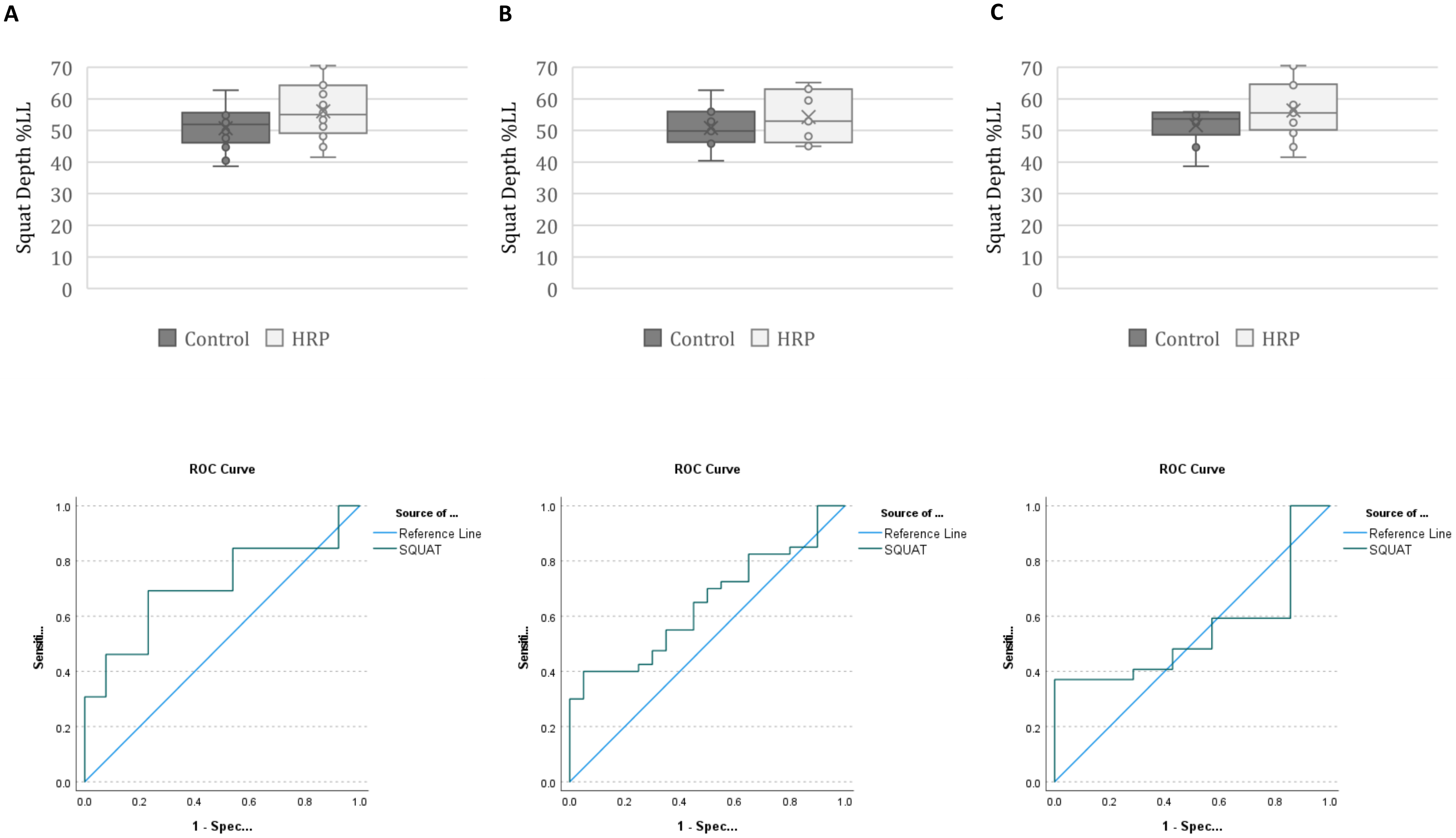


Figure 6-5: Box & whisker plots and corresponding ROC Curves for Squat Depth (%LL, leg length) taken from data collection time point 3. (A) All rowers, (B) Males and (C) Female.

IR ≤30° showed potential predictive ability for identifying those as likely to develop HRP showing high levels of specificity in all categories (0.83 – 1.00) but poor sensitivity values, except for in males (0.46 – 0.71) (See Table 6-14). Although ORs appear promising, the supporting CIs were wide.

Table 6-13: All rowers, internal rotation ≤30° for identification of HRP.

Test Accuracy Outcome	**TP1**	**TP2**	**TP3**	**TP4***
Sensitivity	0.38	0.15	0.26	-
Specificity	0.95	0.83	0.88	-
PPV	0.93	0.67	0.77	-
NPV	0.44	0.31	0.45	-
+ve LR	7.19	0.92	2.28	-
-ve LR	0.66	1.02	0.83	-
OR (± 95%CI)	10.96 (1.31 – 91.32)	0.91 (0.14 – 5.81)	2.74 (0.67 – 11.14)	-

*TP, time point; PPV, positive predictive value; NPV, negative predictive value; +ve LR, positive likelihood ratio; -ve LR, negative likelihood ratio; OR odds ratio; CI, confidence intervals. *hip IR data not collected at this time point due to the impact of Covid-19.*

Table 6-14: Male & female rowers, internal rotation ≤30° for identification of HRP

	Males				Females			
Test Accuracy Outcome	**TP1**	**TP2**[e]	**TP3**	**TP4***	**TP1**	**TP2**	**TP3**	**TP4***
Sensitivity	0.71	-	0.46	-	0.17	0.12	0.16	-
Specificity	0.92	-	0.87	-	1.00	1.00	0.91	-
PPV	0.91	-	0.75	-	1.00	1.00	0.80	-
NPV	0.73	-	0.65	-	0.27	0.29	0.32	-
+ve LR	8.57	-	3.46	-	-	-	1.76	-
-ve LR	0.31	-	0.62	-	0.83	0.88	0.92	-
OR (± 95%CI)	27.50 (2.6–289.2)	-	5.57 (0.9–35.3)	-	-	-	-	-

*TP, time point; PPV, positive predictive value; NPV, negative predictive value; +ve LR, positive likelihood ratio; -ve LR, negative likelihood ratio; OR odds ratio; CI, confidence intervals. *hip IR data not collected at this time point due to the impact of Covid-19. [e] the late inclusion of hip internal rotation as an assessment resulted in gaps in the IR data for the male athletes due to differences in routine screening practices between the sexes.*

Squat Depth of ≥60% LL showed high specificity (0.94 – 1.00) and PPV (0.90 - 1.00) and moderate +LR (4.50 - 7.3) but this was not supported elsewhere (Sn 0.24 - 0.34; NPV 0.39 - 0.50; -ve LR 0.69 – 0.80). Full results for test accuracy are presented in Table 6-15 . A similar pattern was seen for male rowers and female rowers (Table 6-16).

Table 6-15: All rowers, squat depth ≥60% for identification of HRP

Test Accuracy Outcome	TP1	TP2	TP3	TP4
Sensitivity	0.25	0.24	0.34	0.30
Specificity	0.94	0.96	0.95	1.00
PPV	0.90	0.90	0.93	1.00
NPV	0.39	0.43	0.46	0.50
+ve LR	4.50	5.45	7.53	-
-ve LR	0.79	0.80	0.69	0.70
OR (± 95%CI)	5.67 (0.66 – 48.8)	6.83 (0.80 – 58.0)	10.92 (1.32 – 90.5)	-

Table 6-16: Male & female rowers, squat depth ≥60% for identification of HRP.

Test Accuracy Outcome	Males				Females			
	TP1	TP2	TP3	TP4	TP1	TP2	TP3	TP4
Sensitivity	0.46	0.43	0.38	0.09	0.13	0.12	0.32	0.42
Specificity	0.92	0.93	0.92	1.00	1.00	1.00	1.00	1.00
PPV	0.86	0.86	0.83	1.00	1.00	1.00	1.00	1.00
NPV	0.61	0.62	0.60	0.57	0.26	0.29	0.35	0.45
+ve LR	5.54	6.00	5.00	-	-	-	-	-
-ve LR	0.59	0.62	0.67	0.91	0.13	0.12	0.32	0.42
OR (± 95%CI)	9.43 (0.93 – 95.9)	9.75 (0.98 – 96.6)	7.50 (0.73 – 76.8)	-	1.00	1.00	1.00	1.00

TP, time point; PPV, positive predictive value; NPV, negative predictive value; +ve LR, positive likelihood ratio; -ve LR, negative likelihood ratio; OR odds ratio; CI, confidence intervals

6.3.6.3 *Clinical Utility: TL-injuries for HRP*

IR ≤30° showed potential predictive ability for identifying those as likely to develop TL-injuries due to HRP showing high levels of specificity at all time points (0.83 – 0.95) but poor sensitivity values and inconsistent findings for all other prognostic tests. In males, there were also strong positive likelihood ratios (3 – 7.2) and promising, yet inconclusive OR (4.33 – 16.5). See Table 6-17 and Table 6-18.

Table 6-17: All rowers, internal rotation ≤30° for identification of TL-HRP.

Test Accuracy Outcome	**TP1**	**TP2**	**TP3**	**TP4***
Sensitivity	0.31	0.13	0.31	-
Specificity	0.95	0.83	0.88	-
PPV	0.80	0.33	0.57	-
NPV	0.67	0.59	0.72	-
+ve LR	5.85	0.75	2.67	-
-ve LR	0.73	1.05	0.78	-
OR (± 95%CI)	8.0 (0.78 – 82.46)	0.71 (0.05 – 9.50)	3.41 (0.63 – 18.35)	-

*TP, time point; PPV, positive predictive value; NPV, negative predictive value; +ve LR, positive likelihood ratio; -ve LR, negative likelihood ratio; OR odds ratio; CI, confidence intervals. *hip IR data not collected at this time point due to the impact of Covid-19.*

Table 6-18: Male & female rowers, internal rotation ≤30° for identification of TL-HRP.

	Males				Females			
Test Accuracy Outcome	**TP1**	**TP2**	**TP3**	**TP4***	**TP1**	**TP2**	**TP3**	**TP4***
Sensitivity	0.60	-	0.40	-	0.14	0.13	0.25	-
Specificity	0.92	-	0.87	-	1.00	1.00	0.91	-
PPV	0.75	-	0.50	-	1.00	1.00	0.67	-
NPV	0.85	-	0.81	-	0.54	0.56	0.63	-
+ve LR	7.2	-	3	-	-	-	2.75	-
-ve LR	0.44	-	0.69	-	0.86	0.88	0.83	-
OR (± 95%CI)	16.5 (1.19 – 250.2)	-	4.33 (0.43 – 44.4)	-	-	-	3.33 (0.25 – 45.11)	-

*TP, time point; PPV, positive predictive value; NPV, negative predictive value; +ve LR, positive likelihood ratio; -ve LR, negative likelihood ratio; OR odds ratio; CI, confidence intervals. *hip IR data not collected at this time point due to the impact of Covid-19. $^{\theta}$ the late inclusion of hip internal rotation as an assessment resulted in gaps in the IR data for the male athletes due to differences in routine screening practices between the sexes.*

Full results for Squat Depth of ≥60% are presented below in Table 6-19 and Table 6-20 showing high levels of specificity and PPV. Positive LRs and OR were also seen in the analysis of all rowers and the male only group.

Table 6-19: All rowers, squat depth ≥60% for identification of TL-HRP.

Test Accuracy Outcome	TP1	TP2	TP3	TP4
Sensitivity	0.25	0.23	0.46	0.33
Specificity	0.94	0.96	0.95	1.00
PPV	0.75	0.75	0.86	1.00
NPV	0.65	0.69	0.75	0.78
+ve LR	4.5	5.31	10.15	-
-ve LR	0.79	0.80	0.56	0.67
OR (± 95%CI)	5.67 (0.51 – 62.66)	6.6 (0.61 - 71.56)	18 (1.84 – 176.57)	-

Table 6-20: Male rowers, squat depth ≥60% for identification of TL-HRP.

Test Accuracy Outcome	Males				Females			
	TP1	TP2	TP3	TP4	TP1	TP2	TP3	TP4
Sensitivity	0.40	0.40	0.40	0.00	0.13	0.13	0.57	0.60
Specificity	0.92	0.93	0.92	1.00	1.00	1.00	1.00	1.00
PPV	0.67	0.67	0.67	-	1.00	1.00	1.00	1.00
NPV	0.79	0.81	0.80	0.76	0.50	0.56	0.75	0.82
+ve LR	4.8	5.6	5.2	-	-	-	-	-
-ve LR	0.65	0.65	0.65	1	0.875	0.875	0.428571	0.4
OR (± 95%CI)	7.33 (0.48 – 111.2)	8.67 (0.58 – 130.1)	8.0 (0.53 – 120.7)	-	-	-	-	-

TP, time point; PPV, positive predictive value; NPV, negative predictive value; +ve LR, positive likelihood ratio; -ve LR, negative likelihood ratio; OR odds ratio; CI, confidence intervals

6.4 Discussion

6.4.1 Between group comparison

The relationship between intrinsic modifiable risk factors for HRP were examined in an elite rowing cohort. Following univariate assessment, differences were seen in hip IR range of motion and squat depth between those with and without HRP. Rowers who went on to experience HRP tended to have smaller hip IR ranges compared with the control group (mean difference (MD) = 2.4 – 7.8°). The same was seen when comparing TL-HRP to pain-free controls (3.9 – 10.2°). These differences were significant in two of the three reported data-points and the values reported were larger than the SEM reported in Chapter 4. Squat depths were also shallower in both the HRP group (3.9 – 6.3%) and the TL-HRP group (2.9 – 5.9%) compared with the control group. No differences in absolute or relative adduction/abduction strength measures were found for HRP although males experiencing TL-HRP injuries tended to have greater hip strength ratios, in favour of adduction strength, compared with controls (MD = 0.02 – 0.35). The findings of this study support the hypothesis that rowers who go on to develop HRP present with smaller hip ranges of movement and shallower squat depths, but they did not support the hypothesis that strength differences would also be present.

The between-group differences in IR seen in this chapter are comparable with previous literature comparing HRP with controls in pre-surgical candidates (Control, 28 ± 7°; HRP, 23 ± 8°; MD = 5°)(Retchford et al., 2018) as well as between symptomatic and asymptomatic limbs in professional footballers (19° vs 21° respectively)(King et al., 2018), but larger when considering TL-HRP injuries. Tak et al. (2016) reported no differences in IR between footballers with hip-groin symptoms verses controls (*p* = 0.246) but correlated smaller ranges with those most affected as assessed using patient reported outcome measures (PROMs) (23.9 ± 8.7° vs 28.9 ± 7.8°, respectively; *p* = 0.052). However, they included all classifications of hip and groin symptoms not just those related to the hip joint. The IR ranges reported in each of these studies were smaller than seen in this study. This may be explained by the differing mechanical demands and requirements of each cohort or may reflect the fact that rowers were asymptomatic at the point of data collection.

It is believed that restriction of hip range of motion in HRP, often FAIS, is a consequence of bony abutment between the femur and acetabulum in the presence of cam and/or pincer morphology (Mosler, Agricola, et al., 2018). However, recent consensus recommendations from the IHiPRN describe conflicting evidence relating to impairments in hip ROM in HRP (Mosler et al., 2019). This is supported by a systematic review that reported inconsistent findings between-group hip joint IR when comparing those with FAIS and pain-free controls (Freke et al., 2016). These conclusions are often drawn from literature involving people with advanced hip-related pathology. In an athletic cohort, Mosler et al., (2018) found that asymptomatic hips with cam morphology were associated with lower IR ranges. Two studies investigating HRP reported loss of hip IR regardless of cam morphology (Murphy et al., 2017; Tak et al., 2016). Conversely Brunner et al., (2016) found no differences in hip rotation between adolescent ice-hockey player with FAIS, asymptomatic morphology, and controls. These studies were conducted in multidirectional sports involving high levels of movement variability. Rowing is a closed chain, constrained sport with minimal movement variability. Therefore, restrictions in range of movement, with or without bony morphology, may result in higher joint loading and therefore greater risk of developing a symptomatic state than is seen in other sports with similar profiling presentations due to the inability to modify movement to deliver the task.

Squat depth was also shown to be diminished in the HRP-group. This may be due to deficits in mobility, strength and/or stability in the posterior chain (Myer et al., 2014) This finding is comparable to several studies that have shown squat depth to be diminished in subjects with FAIS compared with controls (Lamontagne et al., 2009; Ng et al., 2015; Bagwell et al., 2016; Diamond et al., 2017; Catelli et al., 2018). When squatting, maximum shear stresses on the anterior superior acetabulum have been shown to be significantly higher for individuals with FAIS and severe cam morphology (Ng et al., 2012). This is often associated with a reduction in sagittal plane pelvic motion (Cartelli et al., 2018; Lamontagne et al., 2009; Bagwell et al., 2016) which may indicate avoidance of impingement-based positions. Reductions in squat depth may therefore reflect a strategy to reduce internal joint moments and resultant hip joint loads. Heterogeneity in study methodology makes comparisons of results challenging, with mean differences ranging from 5 to 19%. These studies typically investigated sedentary individuals seeking surgical intervention therefore findings may not apply to elite sporting counterparts. As only frontal plane hip strength was investigated, it is unclear whether deficiencies in posterior hip strength contributed to the reductions seen in squat depth. Previous work has found negative correlations between hip IR and squat depth in males (Kim et al., 2015), *post hoc* analysis in this cohort found no relationship between these variables.

Several systematic reviews have reported reduced hip abduction and adduction strength in HRP (Diamond et al., 2015; Freke et al., 2016; Mayne et al., 2017). This study however found no difference in absolute or relative strength variables between rowers who went on to develop HRP verses controls. This is likely to be due to the differences seen in the age of the participants, their physical activity levels, and their stage of disease progression. Rowers, and more specifically male rowers, tended to have larger hip strength ratios in preference of the hip adductors when considering TL-HRP injuries. Although these findings were not significant. Data in healthy individuals has reported conflicting findings with respect to normal frontal plane strength ratios with some in preference of abductor strength (Kemp et al., 2013) and others adductor (Cahalan et al., 1989). Stronger abductors (Retchford et al., 2018) and adductors (Kemp et al., 2014; Retchford et al., 2018) in HRP patients correlate with better patient reported outcomes including sporting function. These findings reinforce the importance of understanding sport-specific demands placed on the hip musculature in this instance.

When considering the athletic population, one study found no differences in hip strength values between individuals with symptomatic or asymptomatic FAI-morphology or controls (Brunner at al., 2016) while others have found no differences in frontal plane strength in those with HRP (King et al., 2018; Kivlan et al., 2016) and no correlation with cam morphology or dysplasia (Molser et al., 2018). The latter study did however find an association between pincer morphology and an increase in abduction strength (Mosler et al., 2018). It is possible that full-time participation in elite sport, including routine weight training (Gee et al., 2011; Secher, 1993), may enable athletes to maintain relatively symmetrical high levels of muscle strength while asymptomatic.

The hip strength methodology used in this study was shown to have moderate to excellent reliability (section 4.5.3), however the choice of an isometric make-test, may not have been sensitive enough to detect neuromuscular impairments that may present during more dynamic, complex tasks. Sub-elite footballers with HRGP and no hip strength asymmetries, have demonstrated between limb asymmetries during high- and low-load functional tasks (King et al., 2018). It may therefore require more demanding functional tasks to detect any muscular dysfunction. However, as detected in Chapter 5, as rowing is a non-weight bearing task, weight-bearing tasks may not be appropriate in this athletic group to detect differences.

6.4.2 Sex differences

Three of the five variables measured demonstrated sex differences. This supports the rationale for including sex as an effect modifier in the primary analysis. No differences were seen for squat depth or hip abduction strength.

Hip internal rotation was significantly less in males than in female rowers (MD 2.1 – 12.2°, $p < 0.01$). These differences are comparable with two large cohort studies looking at young adults (Laborie et al., 2013) and in college athletes (Czuppon et al., 2016). Both reporting smaller ranges of movement in males. These findings may be a result of sex-specific differences in skeletal geometry and/or due to soft tissue stiffness. Females typically have smaller cam morphology and increased hip versions (both femoral and acetabular) when compared with males (Hetsroni et al., 2013). Males are also known to have a higher prevalence of cam morphology (van Klij et al., 2018) while hip dysplasia is more common in females (LaPrade et al., 2021). Each of these anatomical variants have been shown to be associated with hip rotation (Estberger et al., 2021; Kraeutler et al., 2018; Mosler, Agricola, et al., 2018). Muscles (Blackburn et al., 2004; Martín-San Agustín et al., 2018) and tendons (Fouré et al., 2012) have higher levels of stiffness in males, while ligament structure varies between the sexes (Hashemi et al., 2008) with females demonstrating increased ligament (Shultz et al., 2005) and generalised joint laxity (Jansson et al., 2004). These factors may also have influenced the differences seen in IR.

Male rowers demonstrated significantly larger adductor strength and adduction:abduction strength ratios (MD: 0.55-0.58Nm/kg; ratio 0.22-0.37, $p < 0.01$) but no differences were seen for abduction (MD: -0.08, 0.27Nm/kg, $p > 0.05$). Strength differences between sexes may reflect osseous variations between males and females and therefore resultant moment arms. Németh & Ohlsén (1989) reported significantly longer hip abductor moment arms in males yet of the 3 adductors considered (adductor magnus, hamstrings and gluteus maximus), only the hamstrings were found to have increased moment arm length in males relative to females. Other anatomical variants such as dysplasia (Song et al., 2020) influence moment arm of the hip musculature. In this case by increasing the hip abductor leverage (Song et al., 2020). Radiological assessment is required to clarify this theory and would concurrently allow for identification of muscle volume. This may have further increased understanding but was beyond the scope of this study.

Males may adopt different movement strategies compared with females resulting in higher forces through the adductors. Several studies have found sex-specific kinematics in those with HRP during both low and high impact exercises (Crossley et al., 2021; Grosklos et al., 2022; M. G. King et al., 2019; Lewis, Khuu, et al., 2018; Lewis, Loverro, et al., 2018). High ranges of hip joint flexion are known to correlate with high foot force magnitudes during the rowing stroke, (Buckeridge et al., 2015) while males have a shorter drive phase (Ng et al., 2013), higher peak force and power (McGregor et al., 2008) than females. As adductor magnus acts as a primary hip extensor when the hip is flexed (Neumann, 2010), this may explain the differences seen. Future research should investigate sports-specific movement impairments and biomechanical differences, with the inclusion of EMG, which might help to explain these sex differences in rowers.

6.4.3 Risk factor association & predictive ability

Decreasing hip IR (OR = 0.86 – 0.92) and shallower squat depths (OR = 1.08 – 1.09) were significantly associated with increased risk of HRP. An association was also shown between decreasing hip IR (OR = 0.86 – 0.88) and time-loss injuries due to HRP. Frontal plane hip strength was not found to be a risk factor for HRP or for TL injuries due to HRP. The observed associations seen may increase loading around the hip joint and surrounding tissues during the rowing stroke, potentially contributing to the development of HRP.

Lower hip IR range of motion was associated with HRP. For every 1° less hip rotation, there was an 8 to 14% (95% CI: 0 to 24%) increased chance of having HRP compared with not. However, ROC analysis revealed that hip IR was poor at discriminating between those who would and would not develop HRP (AUC = 0.60 - 0.65). Discriminatory ability was more favourable when considering males and females in isolation (AUC 0.66 – 0.80) although in this instance, associations weren't significant. The same association was seen between decreasing IR and TL-HRP, where a 1° reduction in ROM was associated with a 12 to 14% (95% CI: 1 to 24%) increased chance of having HRP. For TL-injuries, discriminatory ability was poor across the groups.

Shallower squat depths were associated with risk of HRP but not with TL-HRP. Every 1% increase in squat height, was associated with an 8 to 9% (95% CI: 0 to 19%) increased chance of having HRP (AUC = 0.57 – 0.71). This association was not seen when males and females were analysed independently or when pain resulted in time away from training, this may be due to the reduction in sample size as no between sex differences were seen for squat depth.

One previous study investigated the association between musculoskeletal screening tests and the risk of groin injuries in male professional football players (Mosler, Weir, et al., 2018). They found previous hip/groin injuries and eccentric adductor strength were associated with risk of injury. They also identified higher ranges of external rotation as a risk, but no association was seen for IR. Mosler et al., (2018) only included injuries which prevented full participation in training or matches and only 1% of the injuries in this study were classified as hip-related pain. This may in part explain the differences seen.

Based on the findings of this study, the inclusion of prevention strategies which target improvements in hip ROM and squat depth may be beneficial in reducing the development of HRP in elite rowers. However, although associations have been seen, it is prudent to remember that this does not imply causation (Altman & Krzywinski, 2015). Future research should look to explore this concept further using sufficiently powered randomised controlled trials.

6.4.3.1 *Exploratory analysis of clinical utility*

A final objective of this study to was conduct an exploratory analysis considering the clinical utility of factors identified as having an association with higher risk of developing HRP. Bahr et al., (2016) states that screening is unlikely to be able to predict injury due to the substantial overlap of continuous data between high and low risk groups. A fact that is reflected in an example from this study (Figure 6-6 and Figure 6-7). Predetermined thresholds for squat and IR showed potential for identifying those at risk without falsely identifying low-risk individuals, however, except for IR in male rowers, all levels of specificity were accompanied by lower sensitivity meaning a large proportion of those with HRP were not identified.

Dichotomisation of continuous data, as occurred during this final analysis, is frequently discouraged as it leads to oversimplification (Altman & Royston, 2006). For example, it creates the assumption that the difference between 29° IR is vastly different from 31°. Regression analysis is the preferred analytical approach for negating such issues in prediction modelling (Bullock et al., 2021) but the results may not be easily clinically interpretable (Aggarwal & Ranganathan, 2017). In elite sport, where health interventions are costly (Bahr et al., 2016) and marginal gains are critical to overall performance (Hall et al., 2012), considering conservative cut-offs as used in section 1.3.6 may be appropriate.

These results show some potential for further exploration in a larger cohort. However, based on the current level of evidence, these screening assessments are not strong enough to predict those at high risk of injury with certainty.

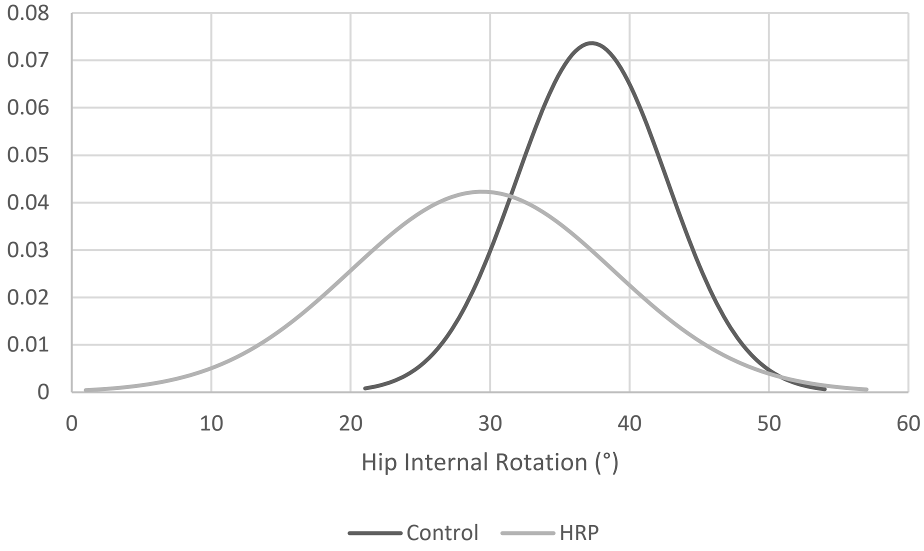


Figure 6-6: Distribution of male Hip IR data from timepoint 1

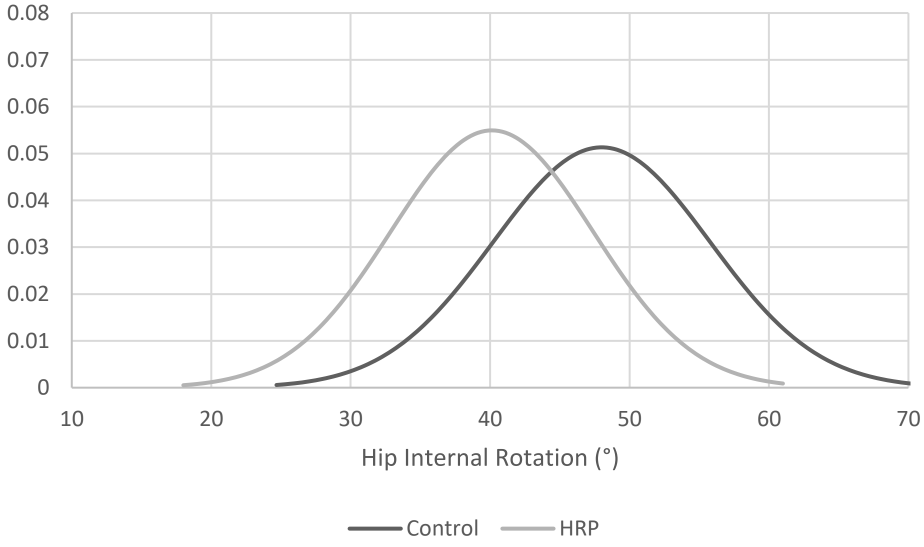


Figure 6-7: Distribution of female Hip IR data from timepoint 1

6.4.4 Strengths & Limitations

To the authors knowledge, this is the first study to explore hip injury risk profiles in an elite rowing cohort. No a priori power analysis was completed, however, this was a cross sectional study of a niche cohort, meaning the sample size was limited to the group of elite rowers available within Great Britain. Having low statistical power means the study was only able to detect strong associations, not small to moderate ones (Bahr & Holme, 2003). It also precluded multivariate assessment. Injury risk prediction is poor when based on single factors alone (Riley et al., 2013) as it is more likely that the interaction of multiple variables create a risk profile, with certain factors modulating or mediating the response (Bittencourt et al., 2016).

Large sample sizes are required to develop robust prediction models (Riley et al., 2020) and may have helped to support or refute our initial hypotheses. Future studies should look to increase participant numbers to conduct a multi-regression analysis. However, this is not feasible in elite-Olympic sport where options to increase numbers would include: multi-national collaboration which is unlikely to increase the sample sufficiently; or inclusion of sub-elite and/or club level athletes which would limit the ecological validity.

Internal rotation and squat depth are both factors which are modifiable if not a consequence of bony morphology. Femoral retroversion is the strongest predictor of IR, more so than the presence of cam morphology (Kraeutler et al., 2018) and is associated with larger labral tears (Ejnisman et al., 2013). Whereas acetabular dysplasia is associated with increased ranges of hip IR (Mosler, Agricola, et al., 2018). The inclusion of radiological imaging may provide greater insight into the risk factors associated with the development of HRP, however, further subclassification of HRP based on bony variants in this study would have underpowered the study further.

The study design did not control for contamination (Hewett, 2017). This includes regulating prevention strategies that may have been implemented based on previous screening exposures or training regimes. Elite rowers are routinely exposed to training designed to develop movement and strength qualities around the hips and trunk to enhance performance and physical robustness (Nugent et al., 2020). These considerations may have diluted the study findings relating to injury risk.

Strengths of the study include the definitions of injury used. Including rowers with HRP that sought medical support but did not experience time loss from training allowed for identification of risk, reflecting the total burden (Bahr et al., 2020). Future research should include exploration of non-modifiable risk factors such as previous injury as this has been identified in other hip/groin related pain (Mosler, Weir, et al., 2018; Ryan et al., 2014; Whittaker et al., 2015). A more in-depth injury classification, including establishing whether injury episodes were recurrent and/or exacerbations will also enhance the quality of epidemiological data and further understanding on risk factor association (Bahr et al., 2020).

6.5 Conclusion

Elite rowers who went on to develop HRP, with and without TL injuries, presented with smaller ranges of hip IR and shallower squat depth compared with controls. There were no differences in isometric adduction:abduction strength profiles.

Significant associations were seen between both hip IR range of motion and squat depth and the development of HRP. Hip IR was the only predictor of TL-HRP injuries in elite rowers. The inclusion of strategies which target improvements in hip ROM and squat depth may therefore be beneficial in reducing the development of HRP in elite rowers. The findings of this study need to be validated in a larger cohort of elite rowers.

6.6 Summary

Chapter 5 identified the association between a series of physical screening assessments and previous HRP in elite rowers. These factors were taken forwards into Chapter 6 to establish the relationship between intrinsic modifiable risk factors and HRP in a prospective cohort of elite rowers.

The development of HRP in elite rowers was associated with lower ranges of hip IR and shallower squats depths compared with healthy controls. This was seen regardless of sex, and regardless of whether an injury required time-loss from training and/or competition or just medical attention. The differences in ROM and squat depth tended to be larger when comparing pain free controls to those experiencing TL-HRP injuries verses those with any HRP, however this was not statisitically analysed due to the overlap in cohorts. Both hip IR and squat depth were also found to be significant predictors of developing HRP, although only changes in hip IR showed an association between the likelihood of experiencing TL-HRP in this cohort of elite rowers.

Male rowers experiencing TL-HRP injuries had higher frontal plane strength ratios compared with pain free controls, with relatively higher isometric adduction strength. No other strength differences were seen between rowers with and without HRP and there was insufficient evidence to confirm an association between strength risk factors and likelihood of developing HRP.

The associations seen in this study for hip IR and squat depth are similar to those seen in pre-surgical groups and other athletic cohorts. However, the absolute values reported do vary which may reflect: differences in methology used, varying stages of disease progression or the difference in physical and biomechanical demands of differing sports. The observed associations seen in ROM and squat depth may increase loading around the hip joint and surrounding tissues during the rowing stroke, potentially contributing to the development of HRP.

An exploratory analysis revealed that predetermined thresholds for squat and IR showed potential for identifying those at risk, however, except for IR in male rowers, all levels of specificity were accompanied by lower sensitivity meaning a large proportion of those with HRP were not identified. Based on the current level of evidence, these screening assessments are not strong enough to predict those at high risk of injury with certainty.

All available and eligible elite British rowers were included in this study. Despite this the sample size remained low which may have have limited the ability to detect smaller associations (Bahr & Holme, 2003). It also precluded multivariate assessment therefore the complex interaction of risk factors was not investigated which is likely to distort the true association between risk factors and the development of HRP (Bittencourt et al., 2016; Riley et al., 2013).

This study was able to identify risk factors for the development of HRP in elite rowers. The inclusion of strategies which target improvements in hip ROM and squat depth may be beneficial in reducing the development of HRP in elite rowers. This will be explored in the next and final experimental chapter. Future research should aim to validate the findings of this prospective study in a larger cohort of elite rowers to ascertain the predictive capabilities of these assessments.

CHAPTER 7

7 PREVENTION OF HRP IN ROWERS USING A TARGETED EXERCISE INTERVENTION: A CASE SERIES

Injury prevention strategies in sports medicine should be guided by clearly identified risk and protective factors as described by Finch (2006) in the Translating Research into Injury Prevention Practice (TRIPP) framework. Chapter 6 identified that shallower squat depths and reduced hip internal rotation were associated with the development of HRP, the latter also being associated with time-loss HRP injuries. The next phase of this thesis is to develop and explore the impact of interventions designed to target these modifiable-risk factors (Finch, 2006).

7.1 Introduction

High quality studies looking at the role of screening and prevention of HRP are lacking (Weir et al., 2015). Literature investigating injury prevention programmes for clinical entities of groin pain, excluding HRP, are more numerous, but have had limited efficacy (Mosler et al., 2015). Despite this, meta-analysis of prevention programmes in footballers estimate an injury reduction of 19-52% (Esteve et al., 2015). While these studies were not deemed to have statistically significant outcomes, they infer a potentially clinically important role.

Impairments in range of motion, muscular strength, and functional deficits are common features in HRP (Griffin et al., 2016; Short et al., 2021). Although causal relationships have not been proven, an association between reduced hip IR and squat depth and the risk of developing HRP in an elite rowing cohort was seen in Chapter 6. To the best of the authors knowledge, no studies have been conducted to investigate the impact of preventative strategies aimed at addressing these factors.

A recent systematic review concluded that physiotherapy-led interventions may improve pain and function in young and middle-aged adults experiencing hip pain, including those with FAIS (Kemp et al., 2020). This is particularly the case when involving an exercise-based approach targeting hip, trunk, and functional strengthening components (J. L. Kemp et al., 2019; Wall et al., 2013). Although the review focused on a symptomatic, often pre-surgical, cohort, several studies included functional outcomes, range of motion and strength with both Palmer et al., (2019) and Coppack et al., (2016a) citing improvements in IR range following the physiotherapy intervention. These studies both included an exercise component targeting movement control and strengthening the trunk and hip. Improvements in squat depth have also been shown following a 6-week exercise intervention in those with FAIS (Wright et al., 2016). Although this study found no differences between those who received manual therapy and a supervised exercise programme to those who received advice and a home exercise programme. Improving hip muscle function during squatting reduces acetabular contact pressures (Cannon et al., 2022) with asymptomatic-FAIS presenting with comparable muscle force patterns to controls which differ from those with FAIS (Catelli et al., 2020). This may explain the improvements seen in squat depth following an exercise-based intervention.

7.1.1 Aims

The previous chapter identified that rowers with restrictions in squat depth and internal rotation were at increased risk of developing HRP. Both are factors which could potentially be modified to reduce injury risk, therefore proactive interventions aimed at improving these outcomes may be of value.

The aim of this chapter is to investigate the effectiveness of a personalised exercise programme, aimed at increasing squat depth and hip IR.

It is hypothesised that completion of a three-month programme will result in improvements in both squat depth and hip ROM. It is also hypothesised that there will be a reduction in time lost from training as compared with historical prevalence and burden data from the Great Britain Rowing Team (in-house injury surveillance data).

7.1.2 Objectives

- To investigate the impact of a 12-week personalised exercise programme on a series of risk factors for HRP in rowers; hip internal rotation and squat depth.
- To ascertain the medium-term impact of the intervention on hip internal rotation and squat depth range at 6-month follow up.
- To understand the impact of an exercise intervention on the development of HRP in athletes identified as being at higher risk. This will be measured using athlete reported outcomes on symptoms and quality of life in relation to HRP.
- To assess the impact of the intervention on athlete availability at the end of the study period. Injury risks and rates will be calculated within the new cohort following the intervention.

7.2 Methodology

Screening data was collected from a new cohort of elite rowers at the Great Britain Rowing Team National Training Centre (NTC). This included assessment of both squat depth and passive hip internal rotation as described in Chapter 3. Rowers were excluded if they were experiencing any lower limb or back injury at the time of assessment or if they were unable to complete the full training programme at the point of screening for any reason.

Rowers were recruited into the case series if they were identified as being at risk of developing HRP. This was established by the following criteria: (1) hip internal rotation ≤30° and (2) double leg (DL) squat depth ≥60% leg length. Injury history was collected at the time of recruitment. Written informed consent was obtained from all rowers (see appendix 10.3). The study received ethical approval from the University of Salford Reasearch ethics committee (ref: HSR1819-049).

7.2.1 Intervention

Study rowers received a personalised exercise programme aimed at improving squat depth and hip IR. The semi-supervised exercise programmes were carried out over a 12-week period as physiotherapy interventions involving targeting strengthening exercises of at least 3 months duration are most effective in improving function and strength in people with HRP (Kemp et al., 2020). Sessions lasted approximately 30 minutes in duration and were carried out 4 times per week. At least one session per week was supervised by a physiotherapist.

Each programme included a specific hip joint mobilisation technique which when applied showed a short-term increase in squat-depth (appendix 10.9). Alongside this, the programmes included targeted, progressive hip and trunk muscle strengthening. A menu of exercises was compiled based on knowledge of impairments seen in HRP which was synthesised throughout the thesis (see appendix 10.10). Each participant's programme was personalised, containing six to eight exercises chosen from the 'menu' which were tailored to the individuals' specific impairments. Exercise selection was based on insight gained from clinical assessment in conjunction with routinely collected (across the sport) hip and trunk strength data to reflect clinical practice. This ensured that each prescription was specific to the individual, which allowed for progressive overload as well as having sufficient variation to ensure the stimulus was challenging yet effective (Medicine, 2009). Exercise prescription was governed by the principles for progressive resistance training outlined in the American College of Sports Medicine position stand (2009). Further detail relating to the intervention is described in Table 7-1 using the Template for Intervention Description and Replication (TIDieR) guidelines (Hoffmann et al., 2014).

During the intervention, rowers continued to participate in the full NTC training programme. This typically included 12 rowing-specific endurance sessions (either on the water or indoor-rowing ergometer) plus weight-room based strength and conditioning sessions, 3 to 4 times per week.

Table 7-1: Intervention delivery described using the TIDieR guidelines

What	Targeted hip mobilisation & progressive strengthening exercise programmes for rowers identified as being at risk of developing HRP: (1) unable to squat below 60%LL and (2) Hip IR ≤30°. Individuals were provided with electronic copy of exercises and a training diary (see appendix 10.11). Details of specific exercises are provided in the appendix 10.10).
Who provided	Profiling data was collected and analysed by the lead author. Programme selection was led and delivered by the squad physiotherapists employed within the NTC, supported by the lead author. Physiotherapists were provided with the study protocols and received training on the process.
How & where	Interventions were initially delivered and coached via 1:1 in person sessions. A mixture of supervised and unsupervised sessions took place at the NTC.
When & how much	Exercise programmes were completed 4 times per week, including one supervised session per week. Exercise programmes were formally reviewed every 4 weeks.
Tailoring	The exercise programmes were personalised so that exercise selection, difficulty level and rate of progression of hip and trunk strengthening was based on individual assessment ascertained during supervised sessions, clinical examination, and targeted assessments.
How well	Adherence to the intervention was recorded on a training diary included on the exercise prescription document

7.2.2 Outcomes

During the primary screening, baseline demographic characteristics were recorded for: sex, age, stature, and mass.

The primary outcomes collected for the duration of the study were: squat depth and hip internal rotation range of movement. The methods for each are described in Chapter 3. These measures were collected every 4-weeks for 12-weeks, then repeated at 6 months to assess the mid-term impact of the intervention on risk factors. Routine in-house injury surveillance monitoring was carried out daily to establish any time loss injuries sustained during the study period. Based on historical data, the expected incidence for the study period was 3 episodes, the expected burden was 24 days. Frequency of outcome collection is show in Table 7-2.

The International Hip Outcome Tool-33 (iHOT-33) was used as a secondary outcome. Patient Reported Outcomes (PROs) are considered the gold standard measure of a patients experience of a health condition and/or treatment (Patrick et al., 2007). The iHOT-33 is one such PRO specifically designed to measure health-related quality of life in young, active patients with hip disorders (Mohtadi et al., 2012) as recommended by the IHiPRN (Impellizzeri et al., 2020). It contains 33 individual questions, each scored on a scale of 0 (worst possible score) to 100 (best possible score) (see appendix 10.12). The iHOT-33 has been shown to be valid, reliable and is highly responsive to clinical change (Mohtadi et al., 2012).

Routinely collected hip and trunk strength assessments, alongside clinical assessment, were used to guide exercise selection decisions. Protocols for hip and trunk assessments are available in Chapter 3.6 and appendix 10.13 respectively.

7.2.3 Analysis

For the initial group screening, mean and standard deviations for the group will be presented. For the case series, a description of the population and outcomes will be provided (Torres-Duque et al., 2020).

Table 7-2: Timeline of measures to be collected.

		Time point (weeks) collected														
Measure	**Purpose**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13-23**	**24**
Age, sex, stature, mass	Baseline characteristics	x														
Squat Depth	Primary Outcome	x				x				x				x		x
IR @90 degrees	Primary Outcome	x				x				x				x		x
Injury Surveillance	Primary Outcome	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
iHOT-33	Secondary Outcome	x				x				x				x		x
Hip strength	Intervention mediator	x												x		
Trunk endurance	Intervention mediator	x												x		
Formal programme review		x				x				x				x		x

7.3 Results

Twenty-seven rowers were initially screened. Of this group, 3 rowers were identified as being at risk of developing HRP (IR ≤30° and squat depth ≥60% leg length). One rower was excluded due to ongoing low-back pain. The two remaining rowers consented to participate in the study. Baseline characteristics and assessments are presented in Table 7-3 and Table 7-4.

Rower 1 had no history of time-loss injuries for HRP although reported he regularly sought soft tissue therapy to help with bilateral hip stiffness. Magnetic resonance imaging (MRI) acquired during the study period reported:

> *'Bilateral cam morphology with anterosuperior marrow oedema, in keeping with a degree of femoroacetabular impingement. No discrete labral tears are identified.'*

Rower 2 reported 1 previous time-loss injury for HRP in the previous season but had been in full training for the previous 8-months. An MRI was carried out at the point of his previous injury in January 2021:

> *'Bilateral cam deformities. Bilateral mild cranial acetabular retroversion. Centre edge angle to the upper limit of normal on the right. These features predispose to cam and pincer-type impingement. Partial anterosuperior labral tear on the left. Right hip labrum appears intact.'*

7.3.1 Primary outcome measures

Primary outcome measures are reported in Table 7-5. Rower 1 presented with bilaterally reduced hip IR. Range of motion did not change during the study period. Rower 2 presented hip reduced hip IR on the left side which increased by 7 to 10°. Both rowers experienced improvements in squat depths during the first 12-weeks of the intervention which was maintained at the 6-month review. Improvements in squat depth were greater than the MDC found in Chapter 4.

Neither rower experienced time loss from training due to HRP during the study period. Rower 1 proactively sought maintenance support for hip range of movement throughout. Of the initial cohort who were profiled, 1 rower experienced training modification for 4 days due to HRP (FAIS).

Table 7-3: Participant characteristics

	Age (years) Mean ± SD	**Sex (M, %)**	**Body Mass (kg) Mean ± SD**	**Stature (cm) Mean ± SD**
All rowers	25 ± 2	27 (59%)	87.5 ± 11.8	189.3 ± 11.8
Rower 1	24	M	94.5	181
Rower 2	26	M	94.6	192

Table 7-4: Baseline physical assessment

	Left IR (°)	**Right IR (°)**	**Squat Depth (%LL)**
All rowers	42.3 ± 10.3	43.8 ± 9.6	52.5 ± 5.7
Rower 1	25	30	61
Rower 2	25	48	64

Table 7-5: Primary outcome measures: Hip Internal Rotation (IR) and Squat Depth

	Baseline	4wks	8wks	12wks	6mths	Difference @12wks	Difference @6mths
Rower 1							
Left IR (°)	25	19	22	24	26	-1	1
Right IR (°)	30	22	22	30	25	0	-5
Squat Depth (%LL)	61	59	50	54	57	7	4
Rower 2							
Left IR* (°)	25	26	28	35	32	10	7
Right IR (°)	48	43	38	49	45	1	-3
Squat Depth (%LL)	64	60	60	58	55	6	9

Wks, weeks; Mths, months; %LL, percentage of leg length

7.3.2 Secondary outcome measures

There was no meaningful change in PROs for either rower as measured using the iHOT-33 when considering the total score (Table 7-6). There was a deterioration in iHOT-Job subscale for rower 1 at both the 12-week (-7 points) and 6-month review (-6 points) but this was outside the SEM and MDC reported for this subscale (9.1 and 25.3 points respectively) (Scholes et al., 2021). Rower 2 had a positive improvement in iHOT-symptoms (+9 points) between baseline and 6-month review which was above the reported SEM (Scholes et al., 2021).

No changes were seen in hip strength scores. Both rower 1 and rower 2 had noticeable improvements in lateral trunk endurance scores (average improvement = 42 seconds).

Table 7-6: Secondary outcome measures: International Hip Outcome Tool (iHOT-33)

		Baseline	**4wks**	**8wks**	**12wks**	**6mths**	**Difference @12wks**	**Difference @6mths**
Rower 1	**iHOT-Total**	**99**	**97**	**96**	**96**	**95**	**-3**	**-4**
	iHOT-Symptoms	157	155	157	157	154	0	-3
	iHOT-Sport	60	60	59	58	59	-2	-1
	iHOT-Job	40	36	34	33	34	-7	-6
	iHOT-Social	70	70	68	68	68	-2	-2
Rower 2	**iHOT-Total**	**94**	**98**	**98**	**95**	**96**	**1**	**2**
	iHOT-Symptoms	148	155	156	150	157	2	9
	iHOT-Sport	58	59	60	58	57	0	-1
	iHOT-Job	35	39	38	37	35	2	0
	iHOT-Social	69	70	68	69	69	0	0

7.4 Discussion

This case series aimed to explore the impact of an exercise-based intervention on a series of risk factors for HRP in elite rowers. Both rowers demonstrated improvements in squat depth, but conflicting findings were seen for hip IR range. Neither participant experienced time-loss due to HRP during the study period. Results of this pilot case series provide initial evidence to support the role of exercise-based strategies in the injury prevention of hip-related pain in elite rowers. Further exploration on a wider scale is required to demonstrate whether targeting modifiable risk factors in this manner impacts injury risk in this cohort.

Squat depth was found to increase following a 12-week hip and trunk strengthening programme (difference of 6° and 7° degrees respectively). These improvements were maintained at the 6-month review (4° and 9°). Wright et al., (2016) found similar positive improvements in squat depth following a 6-week exercise intervention in those with FAIS. In this study, the group who received advice and a home-based exercise programme also showed squat depth improvements however, the improvements seen were superior in the group who received manual therapy and a supervised exercise programme. Despite this finding, 8 of 15 patients (53%) across both groups, proceeded to surgical intervention.

Hip muscle weakness is a common feature of HRP, in those with (Chapter 2.33), and without FAIS (Retchford et al., 2018). Gluteus Maximus (GM) weakness is one proposed mechanism for reductions in squat depth (Ayala et al., 2019; Myer et al., 2014) as greatest activity levels happen during deepest squat ranges where peak torque occurs (Caterisano et al., 2002). In individuals with hip joint pathology, hip extensor moments are reduced when squatting (Bagwell et a., 2016b; Cannon et al., 2022) while muscle atrophy has been demonstrated in both GM (Grimaldi et al., 2009; Malloy, Stone, et al., 2019) and Gluteus Minimus (Malloy, Stone, et al., 2019). Strengthening exercises aimed at improving muscle strength and function of the gluteals may assist in mitigating risk of injury, or delay the progression of pathology associated with HRP (Retchford et al., 2013) by enabling deeper ranges of squat depths and reducing in hip joint loading (Cannon et al., 2022; Lewis et al., 2007). Cannon et al., (2022) found even modest increases in GM and medius activity reduced hip IR and acetabular contact pressures when squatting. Both interventions contained exercises which target primary and secondary hip extensors (Neumann, 2010) which may explain the positive improvements seen in squat depth. However, no meaningful improvements were seen in frontal plane hip strength. Future work would need to include hip extension strength assessments to ascertain if this mechanism was responsible for squat depth improvements.

Due to the methodology employed, it is unclear whether changes in squat depth were a result of changes in hip or pelvic kinetics and kinematics. There are conflicting findings regarding hip kinematics in relation to squat depth in those with HRP. Some reporting associated reductions in hip flexion (Catelli et al., 2021), internal rotation (Bagwell et al., 2026) and adduction (Kumar et al., 2014; Diamond et al., 2017) whereas others found no corresponding difference in hip joint range of motion (Lamontagne et al., 2009). These differences likely reflect the heterogenous nature of the studies. It is possible that improvements in squat depth were a consequence of alterations in trunk muscle function. Both rowers demonstrated positive improvements in trunk endurance assessment. The trunk musculature (rectus abdominus, obliquus external abdominus) contract synergistically with the hip extensors to generate a posterior pelvic tilt motion (Neumann, 2010), it may therefore be this mechanism which is responsible for the improvements seen in squat depth. Several studies demonstrated reduced sagittal plane pelvic motion in those with FAIS compared with both asymptomatic morphology (Catelli et al., 2021; Catelli et al., 2018; Ng et al., 2015) and control populations (Lamontagne et al., 2009; Bagwell et al., 2016;) despite no differences between those with asymptomatic morphology and controls (Catelli et al., 2018, 2021; Ng et al., 2015). Restrictions in pelvic motion when squatting may result in earlier bony abutment of the acetabulum and femoral head-neck junction resulting in increased joint loading. This is associated with decreased hip extensor muscle activity which explains the reduced posterior pelvic tilt positions seen (Bagwell et al., 2016). Catelli et al., (2021) also found differences in squat kinematics were associated with differing muscle contraction strategies. Asymptomatic participants (with and without cam-morphology) had greater posterior hip contact forces and semimembranosus and psoas muscle forces compared to those with FAIS, but lower biceps femoris contributions suggesting potential adaptive behaviours of the hip musculature. These findings may help to understand causation and progression of HRP and suggest that strategies which optimise muscle function and pelvic mobility, as seen in this pilot study, may play an important role in its prevention.

The impact of the intervention on hip IR range of motion was inconclusive. The variation in hip IR seen in rower 1 were within the SEM whereas rower 2 had improvements in hip IR on the problematic side at both 3 and 6 months that were above the MDC reported in Chapter 4. An important consideration here is whether joint range of motion is a modifiable or non-modifiable risk factor (Bahr & Holme, 2003). Previous studies have demonstrated differences in hip IR between those with HRP compared with those with asymptomatic morphology (E. Audenaert et al., 2012; Sink et al., 2008) as well as highlighting the relationship between quality of life and significant reductions in IR (Tak et al., 2016) suggesting that pain and pathology are contributing factors to reductions in motion. However, as this was a prevention-based intervention, the rowers were asymptomatic, dropping only 3 to 12 of a possible 160 points on the iHOT-symptom score. If ROM is a consequence of bony morphology and other anatomical variations such as cam-morphology, versions, or pelvic incidence, it is deemed a non-modifiable risk factor. Femoral mal-version is common in patients with HRP due to FAIS or dysplasia (Lerch et al., 2018) and those with retroverted hips have smaller hip IR ROM (Kraeutler et al., 2018) and larger acetabular labral tears (Ejnisman et al., 2013) compared to those with normal version or anteverted hips. These factors were not taken into consideration in this study therefore it is unknown whether ROM was a modifiable outcome. Although both rowers had more than a 20° difference between hip internal and external rotation ROM which is suggestive of abnormal femoral version (Uding et al., 2018). They also both had confirmed bilateral cam-morphology which has been associated with reductions in hip IR (Mosler et al., 2018; Tak et al., 2016). These findings suggest possible differences in mechanism of movement restrictions in the study rowers.

Two previous studies have reported improvements in hip IR ROM following an individualised physiotherapy programme. Palmer et al., (2019) however included activity modification and Coppack et al., (2016b) involved a 3-week multimodal residential package with no long term follow up. When considering hip flexion ROM, the largest improvements were seen following a 3-month intervention involving strengthening, manual therapy and education (Kemp et al., 2018). The inclusion of manual therapy and other hands-on physiotherapy techniques may have impacted these findings and should be considered in future work. Rower 1 did receive intermittent soft tissue support and showed no meaningful changes in hip IR during the study period. Similar to the findings of this study, Emara et al., (2011) found conservative management resulted in improvements in function but not ROM. Their strategy involved anti-inflammatory medications and avoidance of excessive activity plus stretching. Activity modification is routinely recommended for those with HRP (Griffin et al., 2016; Kemp et al., 2020; Wall et al., 2013), however, the inclusion of activity modification is not conducive in a preventative programme in elite sport whereby the likely inciting event is the sport itself, and high training volumes are deemed as a precursor to performance (Maestu et al., 2005).

The incidence of HRP and time-loss days accrued during the study period across the cohort was less than the predicted incidence and burden. This may have been influenced by the intervention. Neither participant experienced a time-loss injury due to HRP during the study period showing encouraging initial findings in the role of individualised exercise programmes in rowers identified as being at high risk of developing HRP. There was also no meaningful deterioration seen in PROs. Although these findings are promising, this case series is limited by the small number of participants and findings may reflect the limitations of the iHOT-33 which was designed mainly using a surgical cohort (Impellizzeri et al., 2020) with only one recent study investigating its utility in non-surgical candidates (Scholes et al., 2021). It has been acknowledged that the iHOT-33 doesn’t adequately explore the relationship between HRP and sports performance (Scholes et al., 2021). It may be that this PRO measure is not specific enough for an elite athlete cohort.

Rower 1 demonstrated a deterioration in iHOT subscales for ‘job’ despite not showing meaningful changes in other subscales such as for symptoms. This section included questions such as: *How concerned are you that your job will make your hip worse?* Participating in the study itself may have impacted the rower’s perceptions around the perceived risk associated with rowing and the development of HRP. However, this subscale has not been shown to be reliable at either the group or individual level in young to middle-aged adults with hip and/or groin pain, not seeking surgery, requiring a score difference of greater than 25.3 to denote a meaningful change and 10.7 to detect a minimally important change (Scholes et al., 2021). Rower 2 showed a clinically important change in symptoms score at the medium-term review point although this was above the SEM it was below the MDC reported by Scholes et al., (2021). Several authors have reported that the iHOT tool should be used with caution on individual patients due to the large MDC for subscales relative to smaller reported values for interpretability (Impellizzeri et al., 2020; Scholes et al., 2021).

Several of the outcome measures in this study were subject to contamination which may explain the relatively small differences seen in some metrics. As elite rowers, study participants were already exposed to 3 to 5 strength and conditioning sessions per week. This may have influenced the outcomes under investigation (Hewett, 2017) either prior to, or during the study, as exercises which target strength-development around the hip feature strongly to reflect the demands of the sport (Nugent et al., 2020; Rawlley-Singh & Wolf, 2023). Hip range of motion has also been identified as a potential risk factor for low back pain in rowers (Wilson et al., 2021) and as such is heavily factored into and around training sessions (Nugent et al., 2020). Neither of these factors were controlled for which may have therefore influenced the results.

As part of study recruitment, rowers were informed of the aims and objectives of the study. This included athlete education regarding the rationale for the intervention: to investigate the impact of an exercise programme on risk factors for HRP in attempt to reduce their injury risk and optimise their availability to participate in training. This resulted in high levels of compliance and athlete engagement, as rowers were not blinded to the process, however it may also have resulted in bias due to the influence of the Hawthorne effect (McCambridge et al., 2014) which is a further limitation of this study. It is possible that improvements in squat depth were due to adaptations in behaviour rather than the intervention itself.

7.5 Conclusion

An individualised exercise programme improved squat depth in elite rowers identified as being at high-risk of developing HRP over a six-month period but not hip joint IR range. Neither participant experienced time-loss due to HRP during the study period. Results of this pilot case series provide initial evidence to support the role of exercise-based strategies in the prevention of hip-related pain in elite rowers, however, adequately powered studies are required to demonstrate whether targeting modifiable risk factors in this manner impacts injury risk.

7.6 Summary

Risk factor identification is a critical stepping-stone in the wider ambition to prevent sports injuries. Once risk factors, alongside injury mechanisms and exposures have been identified, solutions to address these factors need to be sought (Finch, 2006). Evidence relating to injury prevention programmes for HRP are currently lacking. The previous chapter identified that rowers with restrictions in squat depth and internal rotation were at increased risk of developing HRP. Both are factors which could be modified to reduce injury risk, therefore proactive interventions aimed at improving these outcomes may be important in the prevention of injury. The aim of this chapter was to understand whether an exercise-based intervention was able to positively influence individual injury risk factors for HRP, alongside injury prevalence. Physiotherapy interventions, particularly involving exercise, have previous been shown to be effective on similar outcome measures in a symptomatic cohort (J. L. Kemp et al., 2019; Wall et al., 2013).

Screening data was collected on a new cohort of elite rowers which included hip IR and squat depth. In a cohort of 27 rowers, two individuals were identified as being at high risk and were eligible for the intervention. The rowers were prescribed a personalised exercise programme, which was carried out over a period of 12-weeks alongside their continued participation in the national training programme. Primary outcome measures of hip IR and squat depth were recorded every four weeks during the study period and again after six months to assess both the short- and mid-term impact of the intervention. Injury surveillance was carried out throughout the study period. The iHOT-33, a hip-specific patient reported outcome (PRO) measure, was also collected at the same time points to gain further insight relating to symptoms, activity-impact, and quality of life during, and post-intervention.

A 12-week personalised, exercise-based intervention resulted in improvements in squat depth, which were maintained at six months for both rowers. The mechanisms responsible for improvements in squat depth are not currently clear. Both rowers had positive improvements in trunk capacity but neither showed improvements in frontal plane hip strength. Hip extension strength was not assessed. Due to the methodology employed, it is unknown if alterations in hip or pelvic kinetics or kinematics are responsible for the improvements seen.

The impact of the intervention on hip IR was inconclusive, with Rower 2 showing positive improvements in range of motion in both the short and mid-term, while Rower 1 showed no change at either review. Hip IR was assumed a modifiable risk factor; however, anatomical variations and bone morphology were not taken into consideration. It is therefore unclear whether this is in fact a modifiable outcome measure or not.

Neither rower experienced time loss from training due to HRP during the study period and no meaningful changes were reported in PROs. During the 6-month study period, the incidence of HRP across the cohort of 27 rowers was also less than the pre-anticipated incidence and burden. Limitations of the study include the small sample size and the risk of contamination. Hip range of motion optimisation is heavily factored into and around training sessions (Nugent et al., 2020) as restriction in range have been identified as a potential risk factor for low back pain in rowers (Wilson et al., 2021). Rowers also completed three to five strength and conditioning sessions per week. Both of these factors may have influenced the outcomes under investigation (Hewett, 2017) either prior to, or during the study. As these factors weren't controlled for, they may have influenced the results.

Results of this case series provide initial evidence to support the role of exercise-based strategies in the prevention of HRP in elite rowers. Future research should investigate the role of these interventions in larger cohorts of elite rowers and explore whether targeting modifiable risk factors in this manner impacts injury risk.

CHAPTER 8

8 DISCUSSION

The primary aim of this thesis was to the explore the association between intrinsic risk factors and hip-related pain (HRP) in a cohort of elite rowers. Furthermore, this thesis aimed to advance the understanding of HRP in elite rowers to inform the future screening and injury prevention practices of the Great Britain Rowing Team, and the wider rowing community. The discussion will outline key findings, their value alongside practical applications, and limitations in addition to recommendations for future research.

8.1 Summary of work

The role of injury prevention research has clear benefits to the health and well-being of the athlete (Emery & Pasanen, 2019). In elite rowing, where high volumes of endurance training are considered foundations of successful performance (Maestu et al., 2005), supporting individuals to remain in training by minimising time-loss due to injury is paramount.

Low back pain (LBP) is the most common cause of injury amongst rowers (Hickey et al., 1997; Rumball et al., 2005; Trease et al., 2020), with LBP accounting for 21% of all injury and illness reported over two Olympic cycles (Trease et al., 2020). Comparatively HRP is less common, accounting for 2.8 to 8.4% of total injuries seen (Smoljanovic et al., 2009; Trease et al., 2020), however, increased awareness and understanding of HRP in the orthopaedic and sports medicine community (Weir et al., 2015) has amplified interest in the role that the hip plays in both the health, and performance of an elite rower.

A high prevalence of hip cartilage degeneration (Bittersohl et al., 2019), cam morphology and labral tears has been found in elite rowers (Wedatilake et al., 2021), yet literature relating to HRP in this population remains sparce. Previous literature investigating the sequence of injury prevention (van Mechelen, 1992) of HRP in sport, has been limited to multidirectional, standing sports, with no previous work dedicated to injury prevention, or specifically risk factor identification, in relation to rowing-specific HRP. Consequently, the aims of this field-based thesis are unique.

Due to the absence of literature available on hip health in rowing, Chapter 2 explored femoroacetabular impingement syndrome (FAIS), including accuracy of diagnostics and both physical and functional impairments associated with its presentation. This was necessary to inform the development of the methodology in the forthcoming chapters. Chapter 2 narrowed the focus of HRP to the specific subcategory of FAIS as other manifestations of HRP have not been reported in rowers.

Physical examination is a fundamental component in the diagnosis of HRP and FAIS (Griffin et al., 2016; Weir et al., 2015). However, few diagnostic tests have been shown to have high levels of accuracy, with only FADDIR impingement test, Internal Rotation (IR) at 90° flexion, and FABERs test showing moderate to high levels of sensitivity but poor levels of specificity. Subsequently clinical diagnostic tests can identify inter-articular hip pathology but are unable to detect which structure is responsible. Squatting was the only functional diagnostic test considered, which when used as a pain provocation test had moderate sensitivity, low specificity, and moderate positive and negative likelihood ratios. Although no correlation was found between squat and size of cam-morphology (Murphy et al., 2017), this is the first time that squat depth is referenced as potentially having merit in the identification of those with FAIS.

Exploration of the physical and functional impairments associated with FAIS was a necessary starting point of this work to identify potential intrinsic risk factors for the experimental chapters. Following an extensive review of the literature, section 2.2 identified that range of movement, hip strength, balance, and squat patterns are often altered in the presence of FAIS in comparison with healthy counterparts. Gait and jumping-landing tasks were also found to be affected, although as rowing is a seated, non-impact sport, these assessments were discounted. These findings have also been corroborated by the work of Mosler et al., (2019) within the IHiPRN guidelines in relation to the standardisation of physical capacity measurements in those with HRP.

Although the themes of impairments were consistent, specific findings, especially those pertaining to ROM and strength, were contradictory and often limited to pre-surgical participants, which limits transferability into athletic cohorts. In athletic cohorts, no hip strength differences were found between limbs (King et al., 2018), between participants with symptomatic FAI-morphology and asymptomatic FAI-morphology (Brunner et al., 2016), or between asymptomatic FAI-morphology and controls (Brunner et al., 2016; Mosler, Agricola et al., 2018). With respect to ROM, restrictions were reported when comparing the symptomatic with the asymptomatic limb in adolescent athletic hips (Sink et al., 2008) yet no differences were found between ice hockey players when comparing symptomatic and asymptomatic FAI verses healthy controls (Brunner et al., 2016). The variations seen might be explained by methodological selection of participants from different genders, ages, activity levels and stages of disease progression. This reaffirms the importance of ecological validity when translating research into practice and became a key objective of this work, as it reinforced the need for sport-specific research to be conducted.

Routine imaging was not conducted during the experimental chapters of this thesis as this is not a routine screening practice of the Great Britain Rowing Team and comes with additional financial and logistical considerations. Therefore, subclassification of HRP to: FAIS, dysplasia or other conditions causing hip-related pain without specific bony morphology was not possible (Griffin et al., 2016). As such, from Chapter 3 onwards, FAIS was no longer referred to, but the nomenclature HRP was used.

Chapter 4 sought to ascertain the reliability of a battery of assessments to measure the factors of physical and functional deficits that had been identified in Chapter 2. Reliability was shown to be moderate to excellent for assessments of hip joint IR (intrarater ICC 0.93; interrater ICC 0.92), 2-dimensional squat kinematics (Intrarater ICC 0.90 – 1.00), YBT™ (Intrarater ICC 0.88 – 0.91), single leg squat (Intrarater ICC 0.94) and isometric frontal plane hip strength using a HHD (intrarater ICC 0.85 – 0.92; interrater ICC 0.79 – 0.80). This resulted in a series of assessments with clearly established standard error of measurements which were readily available to inform research results and can easily and confidently be replicated in clinical practice.

Chapter 5 has furthered the body of research by determining the previously unexplored external validity of deficits specifically within a rowing cohort. This was achieved by determining the presence of physical and functional characteristics in rowers with a history of HRP, and ascertaining whether the identified variables had the ability to discriminate between elite rowers with and without a history of HRP.

Rowers with a history of HRP had shallower squat depths (50.5% v 52.5% of leg length), although these differences were not statistically significant, they were outside the SEM and MDC. Percentage of mean squat depth was 1.8 - 2.8% lower in the control group verses individuals with a history of HRP. Findings indicated that although there is substantial overlap between the squat depths achieved in those individuals with a history of injury verses those without, nine individuals (28%) with a history of HRP were unable to squat below 60% leg length compared with only one individual (3%) in the control group. This warranted further investigation to establish whether a pre-determined cut-off value such as this, aids in distinguishing between those who are at high-risk verses low-risk of injury.

Rowers with a history of HRP tended to have reduced ranges of hip IR, furthermore male rowers with a history of HRP had stronger hip adductors and larger YBT reach distances in the posterolateral and medial directions, although these findings were not significant. Male rowers with a history of HRP had significantly smaller ranges of hip IR (HRP 28.8°, Control 36.4°; $p < 0.05$). No other differences were identified in screening assessments between those with and without a history of HRP. As standing dynamic, postural-control is not a sport-specific requirement in rowing, assessments such as the YBT and SL Squat may not be appropriate to detect between group differences in those who have specialised within a non-weight bearing sport, with limited exposure to transferrable balance tasks.

Construct validity was shown when discrete thresholds were used for IR (≤30°) to identify individuals with a history of HRP (Sn 0.67; Sp 0.84; PPV 0.73; NPV 0.80; +ve LR 4.22; -ve LR 0.40; OR 10.67; AUC 0.76), although this was limited to male populations only. Squat depth ≥60% of leg length had a strong association with history of HRP despite lacking sensitivity (Sn 0.27; Sp 0.97; OR 11.63). When multivariate modelling was applied, 17-23% of variance between groups was explained by the screening metrics with only sex and IR being shown to be important in the identification of historical HRP. In this chapter, sex emerged as a critical factor in identifying rowers with a history of HRP, and as such informed the planning and design of screening development stages.

The primary aim of this thesis was to the explore the association between intrinsic risk factors and HRP in a cohort of elite rowers, with chapters 1-5 informing the processes and methodologies required to explore this question within Chapter 6. This study included 55 rowers and 27 HRP injuries, 14 of which resulted in time-loss. Reduced hip IR and shallower squat depths were distinguishing features of rowers with HRP compared to those without. Both factors were associated with increased risk of developing HRP, but only reduced IR was associated with increased likelihood of experiencing time loss due to HRP. Only male rowers experiencing time-loss HRP injuries demonstrated differences in hip strength measures compared with healthy rowers, with larger frontal plane strength ratios and higher isometric hip adduction strength.

Hip IR of ≤30° and squat depth ≥60% leg length was identified as modifiable risk-factors for HRP in Chapter 6. Following the recommendations of van Mechelen and colleagues (1992), Chapter 7 developed and explored the impact of an intervention targeted towards the identified modifiable factors, to close the injury prevention loop. The screening model was applied to twenty-seven rowers. Two rowers were identified as being at high-risk of developing HRP. Although this may seem insignificant, in the context of elite rowing where Olympic finals can be determined by a photo finish (M1x, Rio 2016; LW2x, Tokyo 2021), the identification of these rowers may have meaningful effects on the rowers availability to train and resultant performance outcomes.

Following personalised exercise programmes which were carried out over a period of 12-weeks, both rowers demonstrated improvements in squat depth. Only one demonstrated improvement in hip IR. Neither participant experienced time loss during the 6-month study period and the group incidence and burden of HRP during this time was less than predicted. Results of this study provide initial evidence to support the role of exercise-based strategies in the prevention of HRP in elite rowers, however, these strategies need to be evaluated in larger cohorts to truly understand the role of targeting these risk factors on the development of HRP. Prudently, these are important findings and areas for future investigation. Conservative management should preferentially be the first-line of attack in management of HRP due to the financial burden and risks associated with surgery (Kemp et al., 2020) coupled with the suboptimal post-surgical outcomes associated with return to sport (Ishøi et al., 2018).

8.2 Practical Implications & Recommendations

8.2.1 Risk-factor identification: Hip IR & Squat depth

The main experimental chapter (Chapter 6) identified that restrictions in hip IR and squat depth were associated with the development of HRP in this elite rowing cohort. Both these risk factors are potentially modifiable and could be influenced through low-cost interventions as seen in Chapter 7. Although associations have been identified, it is important to acknowledge the exploratory design of this study does not allow direct causal relationships to be established. However, direct impacts on performance can be noted, which has additional value in an elite athletic population. The findings from this prospective cross-sectional study remain valuable in supporting clinical interpretations, informing preventative interventions, while also addressing previously unanswered gaps in the literature and informing future research practices in elite rowers. A confirmatory study is now required in another cohort of elite rowers, to externally validate the injury risk factors and to investigate a causal relationship (Bahr & Holme, 2003; McCall, 2017).

Reduced hip IR was associated with increased risk of experiencing time-loss HRP injuries in elite rowers. Although hip range of motion has been investigated extensively in a variety of hip and groin clinical presentations (Weir et al., 2015), this is the first study to observe this specifically related to hip-joint related issues in the rowing population. Hip IR has previously been correlated with presence of degenerative lumbar spine disc disease in elite rowers (Wedatilake et al., 2021), reflecting the close and complex relationship seen between the hip and spine (Brown-Taylor et al., 2021). A recent Delphi survey of expert clinicans identified hip range of movement as an important consideration in the management of rowing-specific LBP (Wilson et al., 2021). Future research should investigate the relationship between HRP risk factors identified within this thesis and the development of LBP.

Compared to symptom-free controls, squat depth was found to be reduced in individuals with HRP. Shallower squat depths correlated with increased risk of HRP, with every 1% increase in squat height associated with an 8-9% (95% CI: 0 to 19%) increase in experiencing HRP (AUC = 0.57 – 0.71). Reductions in squat depth have been previously identified in individuals with symptomatic HRP (Lamontagne et al., 2009; Ng et al., 2015; Bagwell et al., 2016; Diamond et al., 2017; Catelli et al., 2018), highlighting the potential role pain in movement dysfunction. As the present squat depth assessments were performed by asymptomatic rowers, this may infer a more causal link between restricted motion and the development of HRP.

The large standard deviations seen in squat depth across all groups of rowers, may be a result of the variations in movement strategies adopted. This may explain why although differences were present, they were not statistically significant. Individuals with FAIS have also demonstrated reduced squat depth when squat patterns are constrained to isolate hip joint motion and limit compensatory contribution from the pelvis and or trunk (Diamond et al., 2019). Rowing, whether on water or on an ergometer, is constrained via attachment of foot position to the foot stretcher. Therefore, a more stringent squatting protocol may have provided further insight. Due to the similarities seen between the triple-extension motion of squatting and the rowing stroke, future research should explore the relationship between HRP and arthro-kinematics in relation to rowing stroke profiles. This may provide further insight into the fundamental role of the hip in both athlete health and sporting performance.

8.2.2 Screening

Initially, this thesis aimed to identify risk factors for HRP, which in turn would contribute to the development and validation of an injury prediction screening tool advocated by Bahr (2016). Despite this endorsed approach (Bahr, 2016) there are significant methodological challenges in validating and conducting multivariate analysis within Olympic and Paralympic cohorts where available population size is relatively small.

Much of the recent debate relating to screening revolves around challenges to its feasibility, efficacy, and role in injury prediction (Bahr, 2016; Hughes et al., 2017), which is often due to inadequate statistical modelling methodology and misinterpretation of association for prediction

(McCall et al., 2017). Following exploratory analysis, IR showed potential merit in the prediction of HRP, however, externally validating these findings in another elite rowing cohort with appropriate statistical modelling would be required to confirm or refute this hypothesis. This was not possible during this thesis. Therefore, it is not possible to advocate using these screening assessments to predict individuals at risk of HRP with a high degree of confidence based on these findings. However, there is agreement that association of measures provide evidence to support implementation of secondary and tertiary injury prevention strategies (McCall, 2017; van Dyk & Clarsen, 2017). It is acknowledged that screening offers several benefits beyond prediction (Mosler et al., 2017; Bahr et al., 2018) such as; identification of an athlete's current health status, collection of baseline athlete-information that supports return to sport and providing the opportunity to establish rapport between athletes and support practitioners (Ljungqvist et al., 2009). Within this study, the assessments employed were shown to have high levels of reliability and low SEM, additionally, associations were found between the development of HRP and assessment of both hip IR and squat depth. The inclusion of these reliable assessments in routine screening practices for rowers, alongside preventative interventions targeted towards optimising these risk factors, is recommended as they can easily and confidently be replicated in future clinical practice and research.

Although clearer direction on how to improve the quality of predictive research in sport is available (Bullock et al., 2021) in the PROGnosis RESearch Strategy (PROGRESS) series (Collins et al., 2015) and the Transparent Reporting of a multivariate prediction model for Individual Prognosis Or Diagnosis (TRIPOD) initiative (Hemingway et al., 2013), they still do not mitigate the challenges of smaller population sizes typically seen in Olympic and Paralympic sports. Stern et al., (2020) likens the prediction of injury to the prediction of the path of a hurricane, *'an imperfect science, but useful enough to guide critical decisions and give estimates'.* Therefore, given the high stakes within high performance sport, despite the limitations and current debate around the challenges of research in this domain, alternative models and methods need to be sought in the quest to identify individuals who are at higher risk of injury to ensure best practice continues to evolve.

8.2.3 Sex-differences

An important finding of this thesis was the differences seen in physical and functional assessments between males and females. Sex was identified as an important confounder when considering history of injury and development of HRP. Males were found to have significantly smaller hip IR (MD: 6.2 – 12.2°, p <0.01), larger hip adduction strength (MD: 0.35 – 0.64 Nm/kg, p <0.01) and frontal plane strength ratios (MD: 0.01 – 0.37, p <0.01) compared with females. This highlights the importance of developing not only sports-specific, but sex-specific screening protocols and that sex-dependent findings should not be transposed between groups. These findings may reflect the known anatomical and morphological differences (Hetsroni et al., 2013; van Klij et al., 2018), or may be due to biomechanical sex-differences which have been reported in both rowers (Buckeridge et al., 2015; McGregor et al., 2008; Warmenhoven et al., 2018) and non-rowers (Crossley et al., 2021; M. G. King et al., 2019; Lewis, Khuu, et al., 2018) or may reflect gender-driven confounders (Nimphius, 2019). Future research needs to consider factors which could contribute to differences in hip joint loading patterns and sex-dependent associations in the research design, to further understand if sex-specific differences are due to differences in training programme prescription, adaptation or technical models or a consequence of sex-specific movement strategies.

8.3 Limitations

A notable limitation of this research was the sample size. Due to the paucity of information in this area, an *a priori* power analysis was not performed for this thesis, but all available and eligible elite British rowers were included.

Recent philosophies acknowledge that injuries are more likely a consequence of a complex interaction of nonlinear, dynamic interdependent factors (Bittencourt et al., 2016; Meeuwisse et al., 2007) and that injury-risk modelling is typically poor when based on single factors alone (Riley et al., 2013). It is probable that the interaction of multiple variables create a risk profile, and that other factors, such as age and sex, modulate or mediate the response and influence an individual's susceptibility (Bittencourt et al., 2016). A convenience sample of all available elite British rowers participated in this study. The resultant participant numbers precluded multivariate statistical analysis, which is likely to distort the true associations and interactions between risk factors and the development of HRP. It would also have limited the ability to detect smaller associations (Bahr & Holme, 2003).

Sample size also prevented assessment of variance within the screening assessments conducted over time which is a limitation as it is known that many intrinsic risk factors are changeable and fluctuate throughout a season (Meeuwisse et al., 2007). This was in part mitigated for by analysing screening assessment relative to the following 6-month time period rather than a complete season.

Sample size is often challenging in elite level Olympic sport where options to increase numbers would include multi-national collaboration, which may not increase the sample sufficiently, and at times is not possible due to perceptions regarding competitive disadvantage; or inclusion of sub-elite and/or club level athletes which would limit the ecological validity. This is not a limitation specific to this thesis but acknowledges the complexity of statistical modelling and challenges associated with the implementation of current screening recommendations in the context of elite athletes. This is a wider challenge associated with the convergence of field-based and academic research.

This is the first known work to explore risk factors for HRP in a seated, non-multidirectional sport which is a major strength of this thesis. There may be opportunities to explore translation of these findings into other sitting based sports such as cycling, canoeing in the kayak discipline and several paralympic sports to determine whether these risk factors are applicable in other sporting activities while attempting to address the aforementioned limitations that arise when working with elite populations.

Much of the terminology relating to HRP, is reflective of several seminal consensus documentations (Griffin et al., 2016; Weir et al., 2015). This language was used to guide the thesis and was echoed in the limited hip-related work that had been conducted in rowing with a key focus of morphology targeting cam or pincer morphology. On reflection, not enough consideration was given to the role that both femoral and acetabular version and other anatomical variations play in the presentation of HRP in the methodological planning. Correlations have been shown between hip IR, femoral and acetabular versions (Chadayammuri et al., 2016; Kraeutler et al., 2018) with femoral retroversion being the strongest predictor of IR range of motion, more so than the presence of cam morphology (Kraeutler et al., 2018). The inclusion of radiology within the protocol may have provided further insight into the potential pathological and morphological presentations associated with HRP in rowers. This was outside the financial and logistical scope of this research.

Increases in anterior tilt, be it bony or dynamic, are predicted to result in the earlier occurrence of impingement (Ross et al., 2014) due to the closely coupled relationship between pelvic tilt position and hip rotation (Bagwell et al., 2016; Ross et al., 2014) which are postulated to contribute to the onset of HRP. As pelvic position is already known to play an important role in rowing performance and rowing-specific spinal health (Buckeridge et al., 2015; Wilson et al., 2021), future work should consider investigating the role of pelvic morphology and kinematics in rowers with HRP, as opportunity to explore pelvic motion effectively during double or single leg squat mechanics was limited within this work.

Following the reliability studies conducted in Chapter 4, challenges relating to rater collection of isometric hip assessment occurred, as with most clinical environments, it was not feasible for a single tester to collect all the hip strength data during the prospective study. The method demonstrated good to excellent intrarater reliability (ICC 0.85 – 0.92) and good interrater reliability (ICC 0.79 – 0.80) however, confidence intervals were wide, showing higher variation in interrater reliability. Whilst multi-rater collection is common in sports science practises, this may have influenced the precision of the data collected and therefore the study outcomes. More reliable assessments such as isokinetic dynamometry (Chamorro et al., 2021; Stark et al., 2011) could have been used, however, this was not deemed time-efficient or effective when assessing large numbers of individuals. Nonetheless, reliability was still within acceptable ranges (Portney & Watkins, 2000) in addition to delivering a method that also provided high clinical utility. The assessment of hip extension, reductions of which have previously been identified in the presence of HRP (Freke et al., 2018; Kierkegaard et al., 2017), was also omitted from this study, as no reliable and efficient assessment compatible with the field-based approach of this research was identified.

8.4 Conclusion

Squat depth and hip joint IR have a key role to play in screening practices within the Great Britain Rowing Team in the prevention, identification, and management of HRP. These assessments will be included in screening assessments conducted throughout the season to identify at-risk athletes, who may require further assessment and multi-disciplinary discussions to determine appropriate interventions. This will increase the likelihood of optimising an athlete's availability to train, therefore enabling them to complete the required training volumes to deliver performance at the elite level.

This work provides insight into the wider multifactorial model of hip-injury in elite rowing by identifying a series of modifiable intrinsic risk factors. Future research could consider external validation of the identified risk factors, variance of assessment profiles and more detailed assessment of pelvic mechanics. This needs to be conducted in conjunction with studies to explore non-modifiable risk factors together with research to explore extrinsic-risk factors and rowing kinematics to establish a complete model of injury aetiology of rowing specific HRP.

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Consensus recommendations on the classification, d. a. d. c. o. h.-r. p. i. y. a. m.-a. a. a. f. t. I. H.-r. P. R. N., Zurich 2018 Michael P Reiman , 1 Rintje Agricola, 2 Joanne L Kemp , 3 Joshua J Heerey , 3 Adam Weir, 4,5 Pim van Klij , 2 Ara Kassarjian, 6,7 Andrea Britt Mosler , 3, Eva Ageberg , P. H. l., 9 Kristian Marstrand Warholm , 10, Damian Griffin, 12 Sue Mayes, 3 Karim M Khan , 13 Kay M Crossley , 3, Mario Bizzini, N. B., 15 Nicola C Casartelli , 16,17 Laura E Diamond , 18 Stephanie Di Stasi , 19 Michael Drew, 20,21 Daniel J Friedman, 22 Matthew Freke, 23 Boris Gojanovic , 24,25 Sion Glyn-Jones, 26 Marcie Harris-Hayes , 15, Michael A Hunt, F. M. I., 28 Lasse Ishøi , 9 Denise M Jones, 3 Matthew G King , 3 Peter R Lawrenson , 29 Michael Leunig, 30 Cara L Lewis , 31 Nicolas Mathieu, 32 Håvard Moksnes, 33 May-Arna Risberg, 34,35, Thorborg, M. J. S. K., . . . Dijkstra, H. P.

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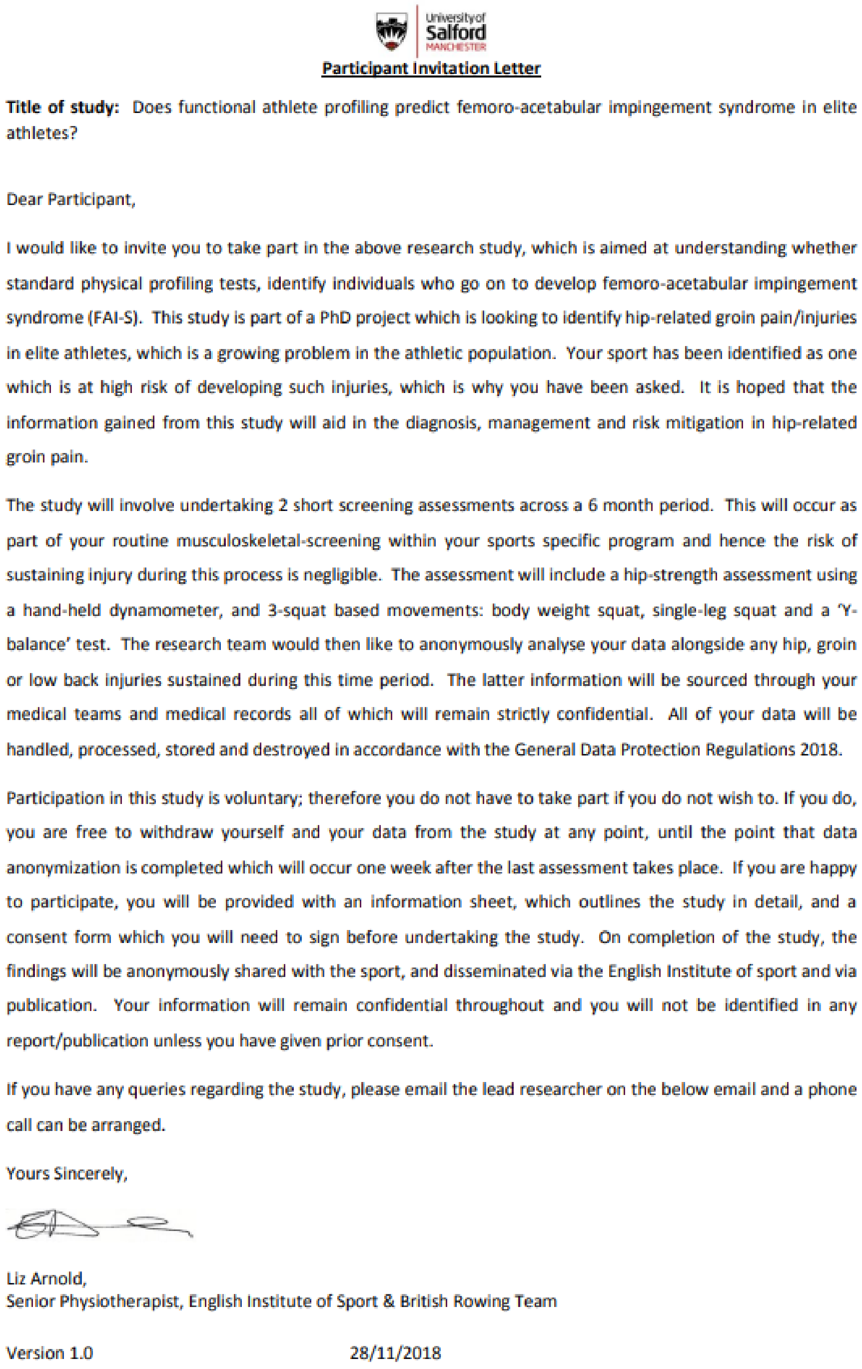
APPENDICIES

10 APPENDICIES

10.1 Participant Invitation Letter



Participant Invitation Letter

Title of study: Does functional athlete profiling predict femoro-acetabular impingement syndrome in elite athletes?

Dear Participant,

I would like to invite you to take part in the above research study, which is aimed at understanding whether standard physical profiling tests, identify individuals who go on to develop femoro-acetabular impingement syndrome (FAI-S). This study is part of a PhD project which is looking to identify hip-related groin pain/injuries in elite athletes, which is a growing problem in the athletic population. Your sport has been identified as one which is at high risk of developing such injuries, which is why you have been asked. It is hoped that the information gained from this study will aid in the diagnosis, management and risk mitigation in hip-related groin pain.

The study will involve undertaking 2 short screening assessments across a 6 month period. This will occur as part of your routine musculoskeletal-screening within your sports specific program and hence the risk of sustaining injury during this process is negligible. The assessment will include a hip-strength assessment using a hand-held dynamometer, and 3-squat based movements: body weight squat, single-leg squat and a 'Y-balance' test. The research team would then like to anonymously analyse your data alongside any hip, groin or low back injuries sustained during this time period. The latter information will be sourced through your medical teams and medical records all of which will remain strictly confidential. All of your data will be handled, processed, stored and destroyed in accordance with the General Data Protection Regulations 2018.

Participation in this study is voluntary; therefore you do not have to take part if you do not wish to. If you do, you are free to withdraw yourself and your data from the study at any point, until the point that data anonymization is completed which will occur one week after the last assessment takes place. If you are happy to participate, you will be provided with an information sheet, which outlines the study in detail, and a consent form which you will need to sign before undertaking the study. On completion of the study, the findings will be anonymously shared with the sport, and disseminated via the English Institute of sport and via publication. Your information will remain confidential throughout and you will not be identified in any report/publication unless you have given prior consent.

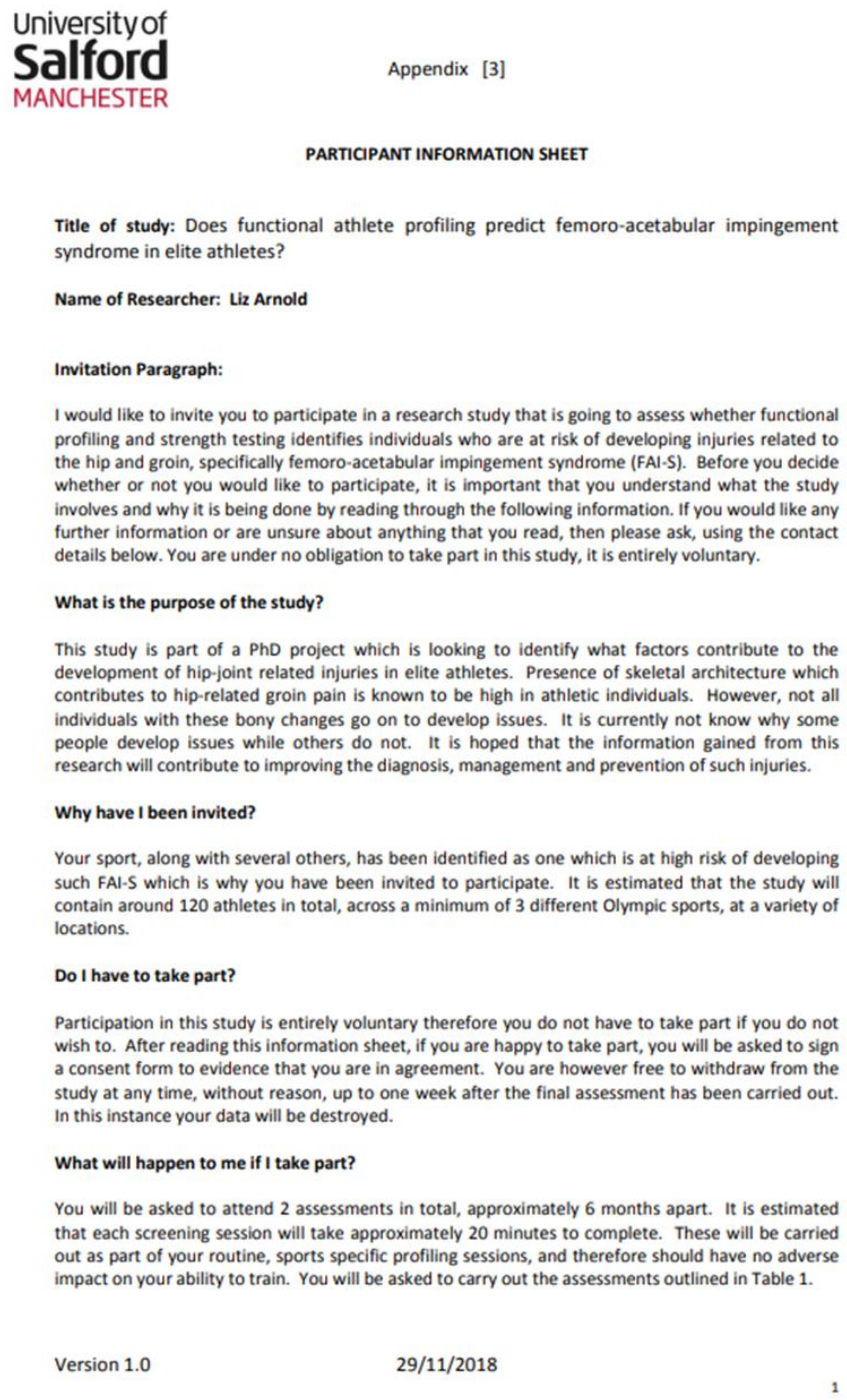
If you have any queries regarding the study, please email the lead researcher on the below email and a phone call can be arranged.

Yours Sincerely,

Liz Arnold,
Senior Physiotherapist, English Institute of Sport & British Rowing Team

Version 1.0 28/11/2018

10.2 Participant Information Sheet



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Appendix [3]

PARTICIPANT INFORMATION SHEET

Title of study: Does functional athlete profiling predict femoro-acetabular impingement syndrome in elite athletes?

Name of Researcher: Liz Arnold

Invitation Paragraph:

I would like to invite you to participate in a research study that is going to assess whether functional profiling and strength testing identifies individuals who are at risk of developing injuries related to the hip and groin, specifically femoro-acetabular impingement syndrome (FAI-S). Before you decide whether or not you would like to participate, it is important that you understand what the study involves and why it is being done by reading through the following information. If you would like any further information or are unsure about anything that you read, then please ask, using the contact details below. You are under no obligation to take part in this study, it is entirely voluntary.

What is the purpose of the study?

This study is part of a PhD project which is looking to identify what factors contribute to the development of hip-joint related injuries in elite athletes. Presence of skeletal architecture which contributes to hip-related groin pain is known to be high in athletic individuals. However, not all individuals with these bony changes go on to develop issues. It is currently not know why some people develop issues while others do not. It is hoped that the information gained from this research will contribute to improving the diagnosis, management and prevention of such injuries.

Why have I been invited?

Your sport, along with several others, has been identified as one which is at high risk of developing such FAI-S which is why you have been invited to participate. It is estimated that the study will contain around 120 athletes in total, across a minimum of 3 different Olympic sports, at a variety of locations.

Do I have to take part?

Participation in this study is entirely voluntary therefore you do not have to take part if you do not wish to. After reading this information sheet, if you are happy to take part, you will be asked to sign a consent form to evidence that you are in agreement. You are however free to withdraw from the study at any time, without reason, up to one week after the final assessment has been carried out. In this instance your data will be destroyed.

What will happen to me if I take part?

You will be asked to attend 2 assessments in total, approximately 6 months apart. It is estimated that each screening session will take approximately 20 minutes to complete. These will be carried out as part of your routine, sports specific profiling sessions, and therefore should have no adverse impact on your ability to train. You will be asked to carry out the assessments outlined in Table 1.

Version 1.0 29/11/2018

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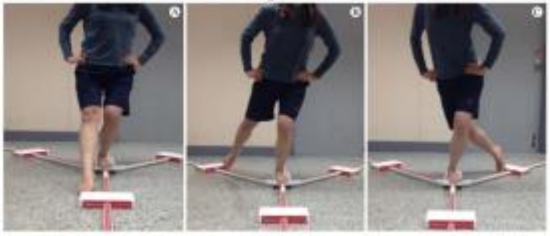
Appendix [3]

Table 1

Assessment	Description
Body Weight Squat	You will be asked to perform 3 unloaded squats to a comfortable depth, while standing with your arms folded across your chest, feet hip distance apart. The squat will be filmed both from behind and from the side for subsequent video analysis.
Single Leg Squat	You will be asked to perform 3 repetitions on each leg. All of which will be filmed for subsequent video analysis.
Y-Balance Test	You will be asked to perform a single leg squat and reach task in the following directions: (as per figure 1.) - Forwards - Back and left - Back and right You will be asked to perform a minimum of 3 repetitions in each direction. Fig.1. 
Hip Abduction Strength	You will be asked to perform 3 maximum isometric contractions, each lasting 3 seconds in duration. Strength will be assessed using a hand-held dynamometer.
Hip Adduction Strength	You will be asked to perform 3 maximum isometric contractions, each lasting 3 seconds in duration. Strength will be assessed using a hand-held dynamometer.

The research team would like to analyse your screening data alongside (i) any injuries sustained to your hip, groin or low back during the same time period, or (ii) any pre-existing hip-related groin issues. With your consent, in the event than an injury, or a recurrence of a pre-existing injury, the team would like to access the following information:

- Diagnosis ± image findings
- Time lost from training

This will be sourced through your medical teams and medical records. All of this information with be handled with care and will remain confidential throughout. This study will in no way interfere with your injury or its management.

What are the possible disadvantages and risks of taking part?

There are no perceived risks or disadvantage in taking part in this study. The risk of sustaining an injury is deemed negligible.

What are the possible benefits of taking part?

You may not directly be influenced by the findings of this study, but it is hoped that the information gained will help to improve the diagnosis, management and prevention of hip related groin injury/pain in aspiring future Olympians.

What if there is a problem?

If you have a concern about any aspect of this study, your experience and/or the researcher, you should ask to speak to the lead researcher (Liz Arnold) who will do her best to answer your questions. If you remain unhappy and wish to complain formally you can do this by contacting the Research Supervisor (Lee Herrington, E: lee.herrington@eis2win.co.uk). If the matter is still not resolved, please forward your concerns to Professor Susan McAndrew, Chair of the Health Research Ethical Approval Panel, Room MS1.91, Mary Seacole Building, Frederick Road Campus, University of Salford, Salford, M6 6PU. Tel: 0161 295 2278. E: s.mcandrew@salford.ac.uk

Will my taking part in the study be kept confidential?

Your participation in the study will be kept entirely confidential by the research team. It is up to you if you choose to disclose your participation with anyone else. All data will be anonymised immediately following assessment and the research team will follow the procedures for handling, processing, storing and destroying of data in accordance with the General Data Protection Regulation 2018.

Immediately after data collection, the data and captured videos will be transferred to the encrypted, password protected computer, of the lead researcher, and it will be backed up on an encrypted, password protected, external hard drive. All information will be anonymously coded and a master list identifying participants to the research codes will be held on the same encrypted, password protected computer which only the lead researcher will have access to. All paperwork collected during the study will be stored in a locked cabinet, within a locked office, accessed only by the lead researcher. No personal or identifying information will be stored.

The data from the study will be stored for 3 years after the completion of the PhD study before being destroyed.

What will happen if I don't carry on with the study?

You are free to withdraw yourself and your data from the study at any point, without reason, up until one week after the last assessment has taken place. In this instance, all your data will be removed from the study and destroyed.

What will happen to the results of the research study?

On completion of the study, the findings will be anonymously shared with the sport, and disseminated via the English Institute of Sport and via publication and presentations. No personal data or identifying images will be revealed (unless prior consent has been sought) and your participation in the study will remain entirely anonymous.

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Appendix [3]

Who is organising or sponsoring the research?

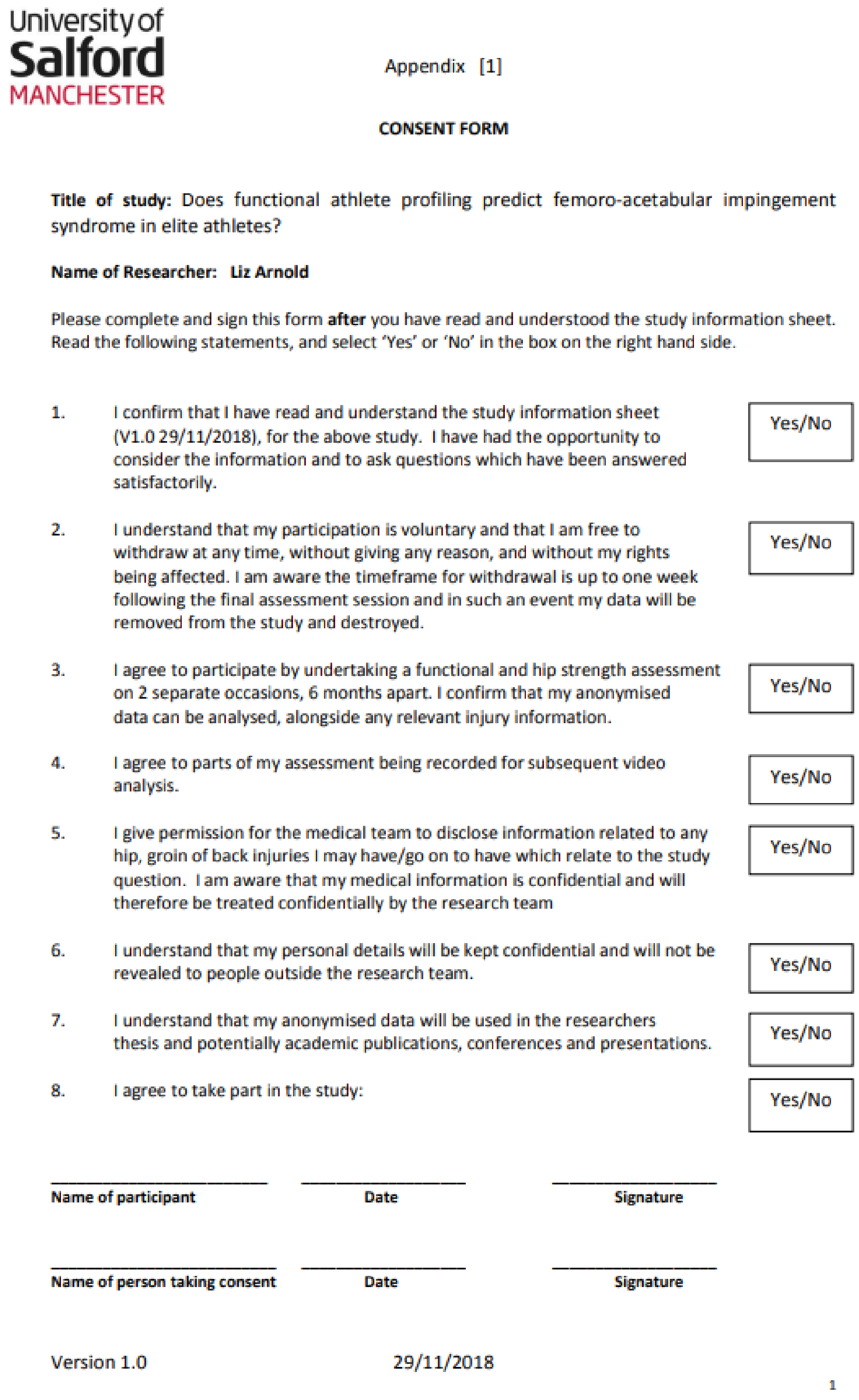
The research is being undertaken as part of a PhD project at Salford University with the support of the English Institute of Sport.

Further information and contact details

Generic research information can be found on the following university website: http://www.salford.ac.uk/research

If you require any further information relating to this project or if you are unsure of your fitness to participate, please email the lead researcher at the following address: liz.arnold@eis2win.co.uk

10.3 Consent Form



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Appendix [1]

CONSENT FORM

Title of study: Does functional athlete profiling predict femoro-acetabular impingement syndrome in elite athletes?

Name of Researcher: Liz Arnold

Please complete and sign this form **after** you have read and understood the study information sheet. Read the following statements, and select 'Yes' or 'No' in the box on the right hand side.

1. I confirm that I have read and understand the study information sheet (V1.0 29/11/2018), for the above study. I have had the opportunity to consider the information and to ask questions which have been answered satisfactorily. Yes/No

2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, and without my rights being affected. I am aware the timeframe for withdrawal is up to one week following the final assessment session and in such an event my data will be removed from the study and destroyed. Yes/No

3. I agree to participate by undertaking a functional and hip strength assessment on 2 separate occasions, 6 months apart. I confirm that my anonymised data can be analysed, alongside any relevant injury information. Yes/No

4. I agree to parts of my assessment being recorded for subsequent video analysis. Yes/No

5. I give permission for the medical team to disclose information related to any hip, groin of back injuries I may have/go on to have which relate to the study question. I am aware that my medical information is confidential and will therefore be treated confidentially by the research team Yes/No

6. I understand that my personal details will be kept confidential and will not be revealed to people outside the research team. Yes/No

7. I understand that my anonymised data will be used in the researchers thesis and potentially academic publications, conferences and presentations. Yes/No

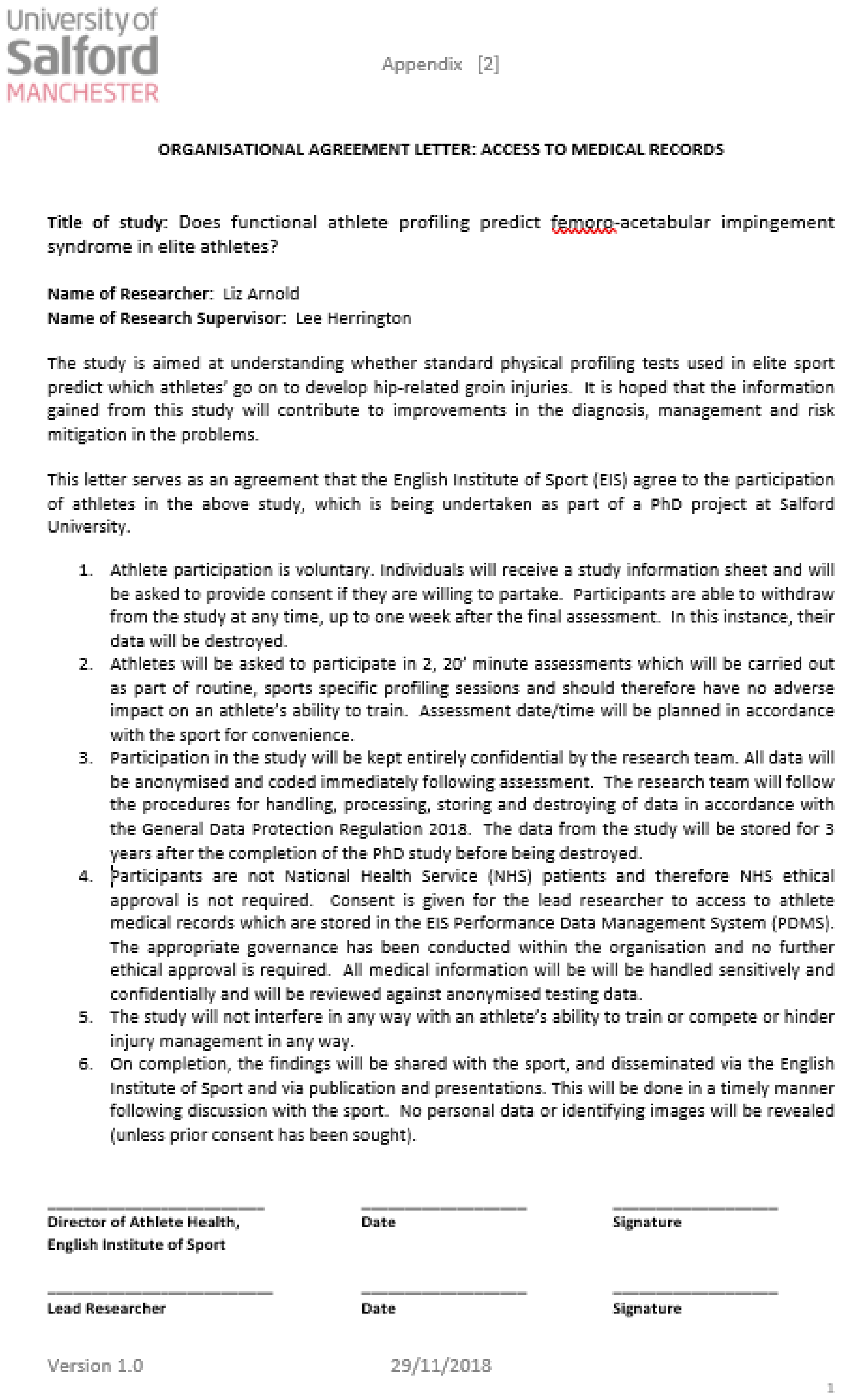
8. I agree to take part in the study: Yes/No

______________________	________________	________________
Name of participant	**Date**	**Signature**
______________________	________________	________________
Name of person taking consent	**Date**	**Signature**

Version 1.0 29/11/2018

1

10.4 Organisational Agreement Letter: access to medical records



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Appendix [2]

ORGANISATIONAL AGREEMENT LETTER: ACCESS TO MEDICAL RECORDS

Title of study: Does functional athlete profiling predict femoro-acetabular impingement syndrome in elite athletes?

Name of Researcher: Liz Arnold
Name of Research Supervisor: Lee Herrington

The study is aimed at understanding whether standard physical profiling tests used in elite sport predict which athletes' go on to develop hip-related groin injuries. It is hoped that the information gained from this study will contribute to improvements in the diagnosis, management and risk mitigation in the problems.

This letter serves as an agreement that the English Institute of Sport (EIS) agree to the participation of athletes in the above study, which is being undertaken as part of a PhD project at Salford University.

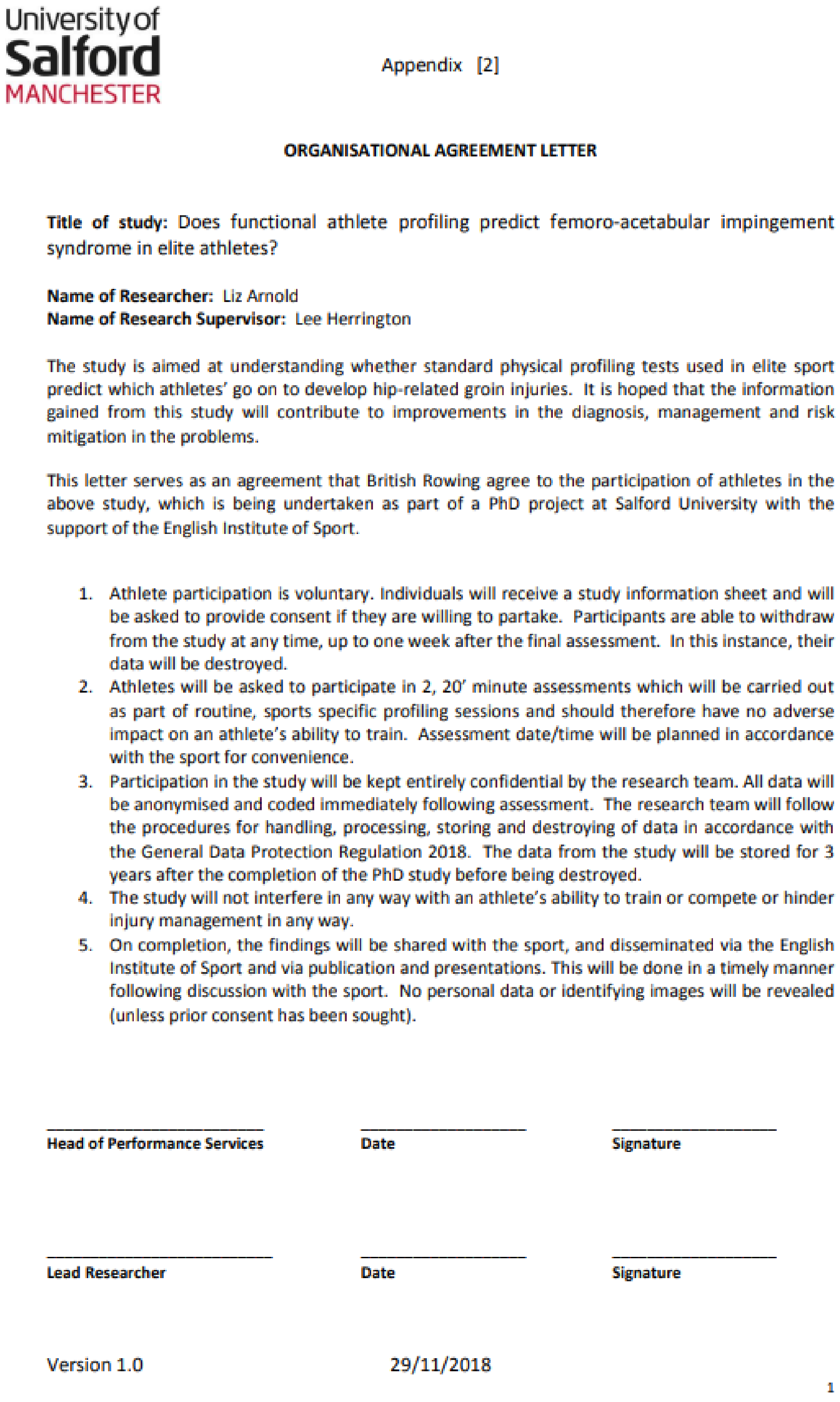
1. Athlete participation is voluntary. Individuals will receive a study information sheet and will be asked to provide consent if they are willing to partake. Participants are able to withdraw from the study at any time, up to one week after the final assessment. In this instance, their data will be destroyed.
2. Athletes will be asked to participate in 2, 20' minute assessments which will be carried out as part of routine, sports specific profiling sessions and should therefore have no adverse impact on an athlete's ability to train. Assessment date/time will be planned in accordance with the sport for convenience.
3. Participation in the study will be kept entirely confidential by the research team. All data will be anonymised and coded immediately following assessment. The research team will follow the procedures for handling, processing, storing and destroying of data in accordance with the General Data Protection Regulation 2018. The data from the study will be stored for 3 years after the completion of the PhD study before being destroyed.
4. Participants are not National Health Service (NHS) patients and therefore NHS ethical approval is not required. Consent is given for the lead researcher to access to athlete medical records which are stored in the EIS Performance Data Management System (PDMS). The appropriate governance has been conducted within the organisation and no further ethical approval is required. All medical information will be will be handled sensitively and confidentially and will be reviewed against anonymised testing data.
5. The study will not interfere in any way with an athlete's ability to train or compete or hinder injury management in any way.
6. On completion, the findings will be shared with the sport, and disseminated via the English Institute of Sport and via publication and presentations. This will be done in a timely manner following discussion with the sport. No personal data or identifying images will be revealed (unless prior consent has been sought).

_______________________ **Director of Athlete Health,** **English Institute of Sport**	_________________ **Date**	_________________ **Signature**
_______________________ **Lead Researcher**	_________________ **Date**	_________________ **Signature**

Version 1.0 29/11/2018

1

10.5 Organisational Agreement Letter



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Appendix [2]

ORGANISATIONAL AGREEMENT LETTER

Title of study: Does functional athlete profiling predict femoro-acetabular impingement syndrome in elite athletes?

Name of Researcher: Liz Arnold
Name of Research Supervisor: Lee Herrington

The study is aimed at understanding whether standard physical profiling tests used in elite sport predict which athletes' go on to develop hip-related groin injuries. It is hoped that the information gained from this study will contribute to improvements in the diagnosis, management and risk mitigation in the problems.

This letter serves as an agreement that British Rowing agree to the participation of athletes in the above study, which is being undertaken as part of a PhD project at Salford University with the support of the English Institute of Sport.

1. Athlete participation is voluntary. Individuals will receive a study information sheet and will be asked to provide consent if they are willing to partake. Participants are able to withdraw from the study at any time, up to one week after the final assessment. In this instance, their data will be destroyed.
2. Athletes will be asked to participate in 2, 20' minute assessments which will be carried out as part of routine, sports specific profiling sessions and should therefore have no adverse impact on an athlete's ability to train. Assessment date/time will be planned in accordance with the sport for convenience.
3. Participation in the study will be kept entirely confidential by the research team. All data will be anonymised and coded immediately following assessment. The research team will follow the procedures for handling, processing, storing and destroying of data in accordance with the General Data Protection Regulation 2018. The data from the study will be stored for 3 years after the completion of the PhD study before being destroyed.
4. The study will not interfere in any way with an athlete's ability to train or compete or hinder injury management in any way.
5. On completion, the findings will be shared with the sport, and disseminated via the English Institute of Sport and via publication and presentations. This will be done in a timely manner following discussion with the sport. No personal data or identifying images will be revealed (unless prior consent has been sought).

________________________	__________________	__________________
Head of Performance Services	**Date**	**Signature**
________________________	__________________	__________________
Lead Researcher	**Date**	**Signature**

Version 1.0 29/11/2018

1

10.6 Other causes of groin pain

An overview of some of the ‘Other’ possible causes of groin pain in athletes. Taken from: Doha agreement meeting on terminology and definitions in groin pain in athletes (Weir et al., 2015)

Table 10-1 Other possible causes of groin pain

Other musculoskeletal causes	Not to be missed
Inguinal or femoral hernia Post hernioplasty pain Nerve entrapment ▸ Obturator ▸ Ilioinguinal ▸ Genitofemoral ▸ Iliohypogastric Referred pain ▸ Lumbar spine ▸ Sacroiliac joint Apophysitis or avulsion fracture ▸ Anterior superior iliac spine ▸ Anterior inferior iliac spine ▸ Pubic bone	Stress fracture ▸ Neck of femur ▸ Pubic ramus ▸ Acetabulum Hip joint ▸ Slipped capital femoral epiphysis (adolescents) ▸ Perthes’ disease (children and adolescents) ▸ Avascular necrosis/transient osteoporosis of the head of the femur ▸ Arthritis of the hip joint (reactive or infectious) Inguinal lymphadenopathy Intra-abdominal abnormality ▸ Prostatitis ▸ Urinary tract infections ▸ Kidney stone ▸ Appendicitis ▸ Diverticulitis Gynaecological conditions Spondyloarthropathies ▸ Ankylosing spondylitis Tumours ▸ Testicular tumours ▸ Bone tumours

10.7 Strength assessment warm up

Table 10-2: Standardised warm up for hip strength assessment

Exercises	**Volume**
Hip Rotations	1 x 10
Straight Leg Raises	1 x 10
Adductor Rock Backs	1 x 5 each side
Sumo Squat	1 x 10
Split Squat	1 x 5 each side

10.8 Frontal plane, isometric hip strength data in Sweep rowers: Comparison of inside leg verses outside leg.

Table 10-4: Pilot data to explore between limb differences in frontal plane, isometric hip strength in sweep oar rowers.

		Inside Leg	**Outside Leg**	***p*- value**	***r***
All Sweep	**Abduction (Nm/kg)**	2.44 ± 0.40	2.34 ± 0.42	0.46	0.85
	Adduction (Nm/kg)	2.45 ± 0.61	2.54 ± 0.72	0.68	0.91
Male Sweep	**Abduction (Nm/kg)**	2.42 ± 0.43	2.35 ± 0.39	0.69	0.87
	Adduction (Nm/kg)	2.70 ± 0.64	2.77 ± 0.78	0.84	0.92
Female Sweep	**Abduction (Nm/kg)**	2.47 ± 0.36	2.33 ± 0.46	0.54	0.85
	Adduction (Nm/kg)	2.09 ± 0.33	2.22 ± 0.48	0.56	0.84

r = Pearson correlation coefficients

10.9 Within session effects of self-administered mobilsations with movement (sMWM) in relation to squat depth

10.9.1 Method

The same participants were recruited as used in the initial screening in Chapter 7: case series whereby baseline participant characteristics and consent were obtained.

Squat depth assessments were carried out as the final screening in a battery of other musculoskeletal assessments. The methodology is described in Chapter 3. Data was only collected with the camera directly behind the participant to collect squat depth from the PSIS.

Following initial squat assessment each participant performed a self-administered mobilisation with movement (sMWM). The participant was set up in four-point kneeling starting in 90° hip flexion, in front of a squat rack. The head of the participant facing away from the squat rack. A heavy resistance band (Medium Green Pullum™ Resistance Band: 50-120lbs, 44mm wide) was positioned as proximally on the femur as comfortably possible, towards the groin crease, with the other end attached to the vertical beam of a squat rack, perpendicular to the thigh.

The participant was asked to move (crawl) forwards until tension is detected in the band stimulating a caudal glide to the femur. The participant was then instructed to rock forwards (opening the hip angle >90°) and backwards (sitting towards the heels). All sMWMs were supervised by the same therapist to ensure motion in the sagittal plane. Participants were instructed to inform the tester if there was any pain or discomfort during the exercise. Minor adjustments were made to the band position to ensure pain free movement was achieved. The participant was asked to perform 3 sets of 10 repetitions as recommended by Mulligan (Hing et al., 2009; Mulligan, 2006) with 30 seconds rest between sets. Immediately following the sMWM, 3 bodyweight squats were repeated.

10.9.2 Results

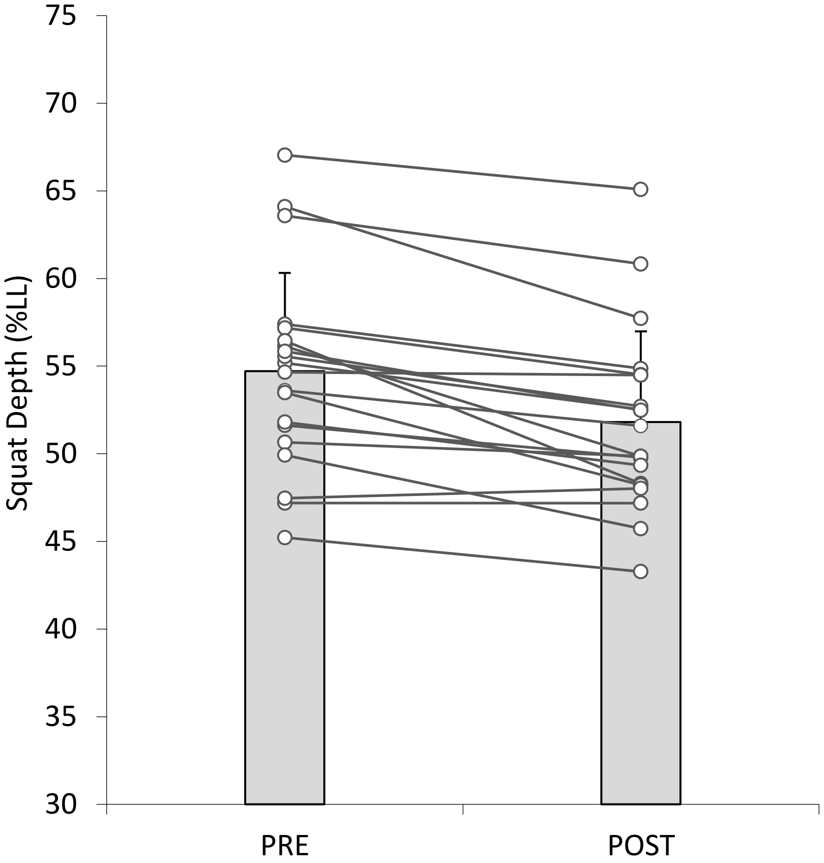
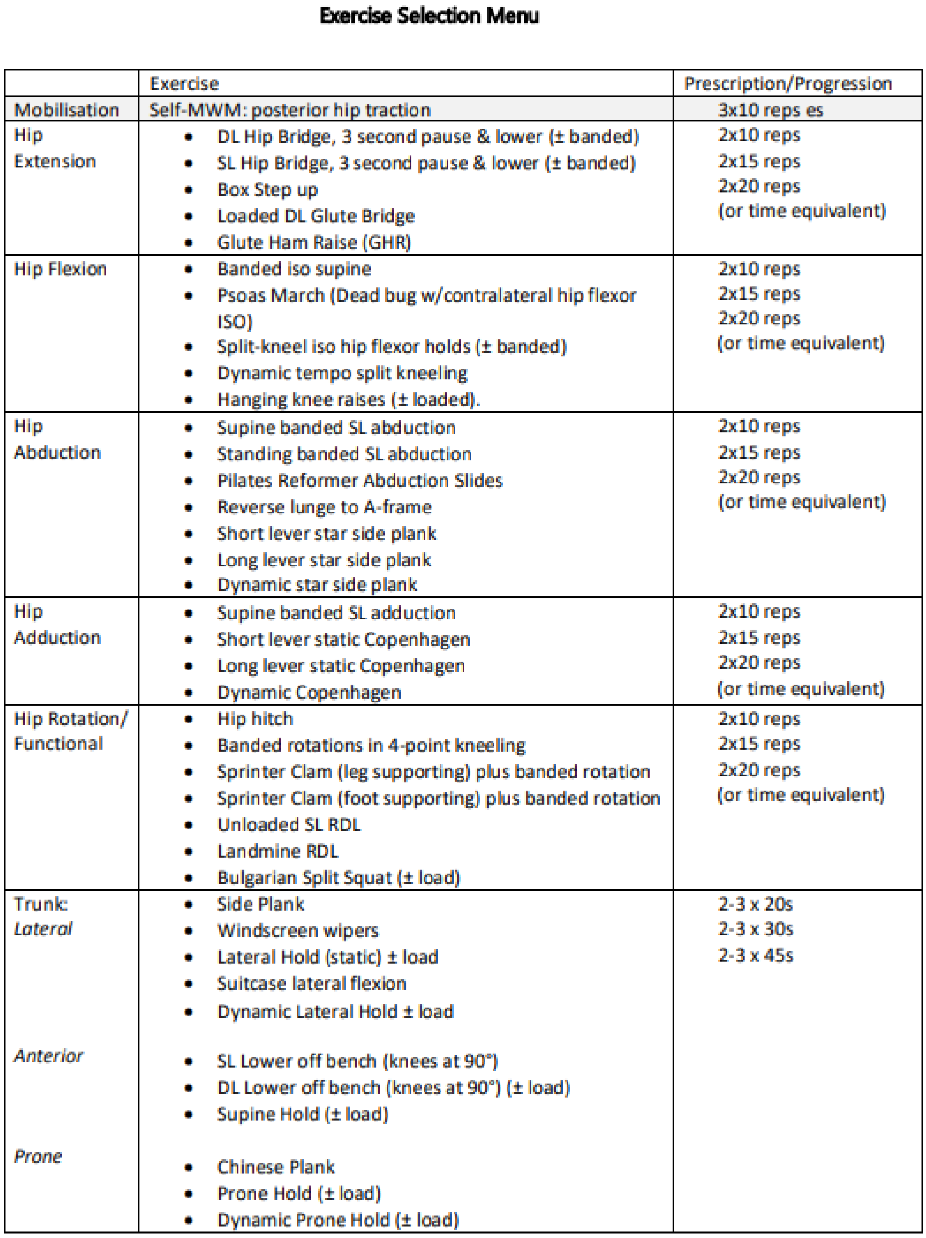


Figure 10-1: Squat depth pre and post sMWM.

10.10 Exercise Menu



Exercise Selection Menu

	Exercise	Prescription/Progression
Mobilisation	Self-MWM: posterior hip traction	3x10 reps es
Hip Extension	• DL Hip Bridge, 3 second pause & lower (± banded) • SL Hip Bridge, 3 second pause & lower (± banded) • Box Step up • Loaded DL Glute Bridge • Glute Ham Raise (GHR)	2x10 reps 2x15 reps 2x20 reps (or time equivalent)
Hip Flexion	• Banded iso supine • Psoas March (Dead bug w/contralateral hip flexor ISO) • Split-kneel iso hip flexor holds (± banded) • Dynamic tempo split kneeling • Hanging knee raises (± loaded).	2x10 reps 2x15 reps 2x20 reps (or time equivalent)
Hip Abduction	• Supine banded SL abduction • Standing banded SL abduction • Pilates Reformer Abduction Slides • Reverse lunge to A-frame • Short lever star side plank • Long lever star side plank • Dynamic star side plank	2x10 reps 2x15 reps 2x20 reps (or time equivalent)
Hip Adduction	• Supine banded SL adduction • Short lever static Copenhagen • Long lever static Copenhagen • Dynamic Copenhagen	2x10 reps 2x15 reps 2x20 reps (or time equivalent)
Hip Rotation/ Functional	• Hip hitch • Banded rotations in 4-point kneeling • Sprinter Clam (leg supporting) plus banded rotation • Sprinter Clam (foot supporting) plus banded rotation • Unloaded SL RDL • Landmine RDL • Bulgarian Split Squat (± load)	2x10 reps 2x15 reps 2x20 reps (or time equivalent)
Trunk: *Lateral*	• Side Plank • Windscreen wipers • Lateral Hold (static) ± load • Suitcase lateral flexion • Dynamic Lateral Hold ± load	2-3 x 20s 2-3 x 30s 2-3 x 45s
Anterior	• SL Lower off bench (knees at 90°) • DL Lower off bench (knees at 90°) (± load) • Supine Hold (± load)	
Prone	• Chinese Plank • Prone Hold (± load) • Dynamic Prone Hold (± load)	

10.11 Programme Examples

NAME: Rower 1

PROGRAMME GOALS: Functional hip stability, hip Adduction strength, lateral trunk capacity

	Notes	Date	27/09/21 Week 1				04/10/21 Week 2				11/10/21 Week 3				18/10/21 Week 4			
		Volume	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Self MWM hip traction		3x10 es																
Hip hitch +rotation/flex		2x8es																
Sprinter Clam + band		2x8es																
Loaded Bulgarian		2x12es																
Loaded lateral holds		3x30s																
Windscreen Wipers	+ pelvis lift	2x12 es																

NAME: Rower 2 **PROGRAMME GOALS:** Hip Abd/Add Strength, Lateral & Prone Trunk Endurance

	Notes	Date	27/09/21 Week 1				04/10/21 Week 2				11/10/21 Week 3				18/10/21 Week 4			
		Volume	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Self MWM hip traction		3x10 es																
Tempo'd Bulgarian	3,3,1,1 tempo	2x6 es																
Supine banded hip flex ISO		2x30s																
Long lever copenhagen		2x30s																
Standing banded SL ABDuction		2x15																
Banded Prone hold		2x30s																
Loaded DL Lowers		2x30s																
Lateral Hold with load		2x30s																

BRITISH ROWING

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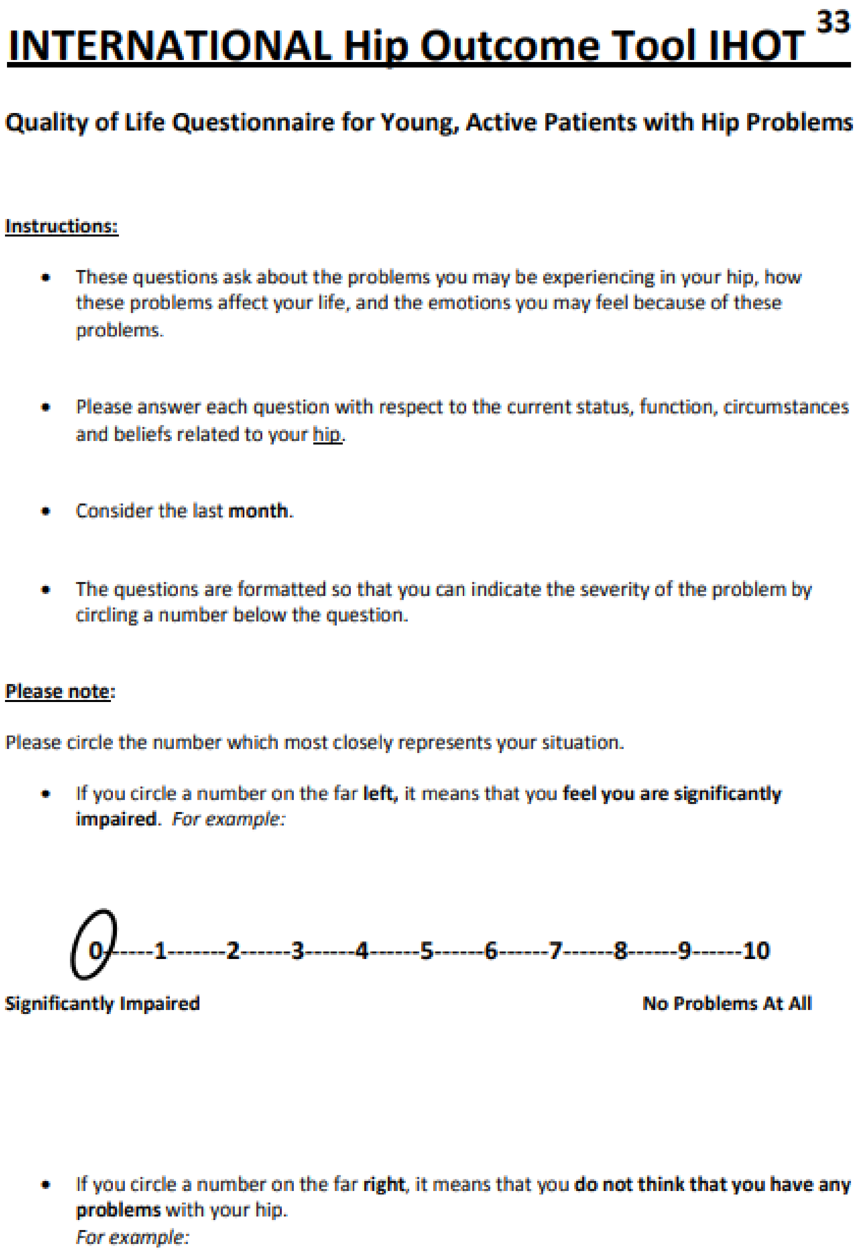
10.12 iHOT-33 Questionnaire



INTERNATIONAL Hip Outcome Tool IHOT ^{33}

Quality of Life Questionnaire for Young, Active Patients with Hip Problems

Instructions:

- These questions ask about the problems you may be experiencing in your hip, how these problems affect your life, and the emotions you may feel because of these problems.
- Please answer each question with respect to the current status, function, circumstances and beliefs related to your hip.
- Consider the last **month**.
- The questions are formatted so that you can indicate the severity of the problem by circling a number below the question.

Please note:

Please circle the number which most closely represents your situation.

- If you circle a number on the far **left,** it means that you **feel you are significantly impaired**. *For example:*

[✓ 0]-----1-------2------3------4------5------6------7------8------9------10

Significantly Impaired **No Problems At All**

- If you circle a number on the far **right**, it means that you **do not think that you have any problems** with your hip.
  For example:

0------1-------2------3------4------5------6------7------8------9-----[✓ 10]

Significantly Impaired **No Problems At All**

If a number is circled in the middle of the line, this indicates that you are moderately disabled, or in other words, between the extremes of 'significantly impaired' and 'no problems at all'. It is important to circle a number at the appropriate end of the line if the extreme descriptions accurately reflect your situation.

If the question asks about something that you do not experience, please mark the option:

☑ **I do not do this action in my activities**, where this is appropriate.

I: SYMPTOMS AND FUNCTIONAL LIMITATIONS

The following questions ask about symptoms that you may experience in your **hip** and about the function of your **hip** with respect to daily activities. Please think about how you have felt most of the time over the past **month** and answer accordingly.

1. How often does your hip/groin ache?

0------1-------2------3------4------5------6------7------8------9------10

Constantly **Never**

2. How stiff is your hip as a result of sitting/resting during the day?

0------1-------2------3------4------5------6------7------8------9------10

Extremely Stiff **Not Stiff At All**

3. How difficult is it for you to walk long distances?

0------1-------2------3------4------5------6------7------8------9------10

Extremely Difficult **Not Difficult At All**

4. How much pain do you have in your hip while sitting?

0------1-------2------3------4------5------6------7------8------9------10

Extreme Pain	**No Pain At All**

5. How much trouble do you have standing on your feet for long period of time?

0------1-------2------3------4------5------6------7------8------9------10

Severe Trouble	**No Trouble At All**

6. How difficult is it for you to get up and down off the floor/ground?

0------1-------2------3------4------5------6------7------8------9------10

Extremely Difficult	**Not Difficult At All**

7. How difficult is it for you to walk on uneven surfaces?

0------1-------2------3------4------5------6------7------8------9------10

Extremely Difficult	**Not Difficult At All**

8. How difficult is it for you to lie on your affected hip side?

0------1-------2------3------4------5------6------7------8------9------10

Extremely Difficult **Not Difficult At All**

9. How much trouble do you have with stepping over obstacles?

0------1-------2------3------4------5------6------7------8------9------10

Severe Trouble **No Trouble At All**

10. How much trouble do you have climbing up/downstairs?

0------1-------2------3------4------5------6------7------8------9------10

Severe Trouble **No Trouble At All**

11. How much trouble do you have with rising from a sitting position?

0------1-------2------3------4------5------6------7------8------9------10

Severe Trouble **No Trouble At All**

12. How much discomfort do you have with taking long strides?

0------1-------2------3------4------5------6------7------8------9------10

Extreme Discomfort **No Discomfort At All**

13. How much difficulty do you have with getting into and/or out of a car?

0 ------1-------2------3------4------5------6------7------8------9------10

Extreme Difficulty **No Difficulty At All**

14. How much trouble do you have with grinding, catching, or clicking in your hip?

0------1-------2------3------4------5------6------7------8------9------10

Severe Trouble **No Trouble At All**

15. How much difficulty do you have with putting on/taking off socks, stockings, or shoes?

0------1-------2------3------4------5------6------7------8------9------10

Extreme Difficulty **No Difficulty At All**

14. Overall, how much pain do you have in your hip/groin?

0------1-------2------3------4------5------6------7------8------9------10

Extreme Pain **No Pain At All**

II: SPORTS AND RECREATIONAL ACTIVITIES

The following questions ask about your **hip** when you participate in sports and recreational activities. Please think about how you have felt most of the time over the past **month** and answer accordingly.

17. How concerned are you about your ability to maintain your desired fitness level?

0------1-------2------3------4------5------6------7------8------9------10

Extremely Concerned **Not Concerned At All**

18. How much pain do you experience in your hip <u>after</u> activity?

0------1-------2------3------4------5------6------7------8------9------10

Extreme Pain **No Pain At All**

19. **How concerned are you that the pain in your hip will increase if you participate in sports or recreational activities?**

0------1-------2------3------4------5------6------7------8------9------10

Extremely Concerned **Not Concerned At All**

20. **How much was your quality of life deteriorated because you cannot participate in sport/recreational activities?**

0------1-------2------3------4------5------6------7------8------9------10

Extremely Deteriorated **Not Deteriorated At All**

21. **How concerned are you about cutting/changing directions during your sports or recreational activities?**

☐ **I do not do this action in my activities.**

0------1-------2------3------4------5------6------7------8------9------10

Extremely Concerned **Not Concerned At All**

22. **How much has your performance level decreased in your sport or recreational activities?**

0------1-------2------3------4------5------6------7------8------9------10

Extremely Decreased **Not Decreased At All**

III: JOB RELATED CONCERNS

The following questions relate to your **hip** with respect to your work or occupational activities. Please think about how you have felt most of the time over the past **month** and answer accordingly.

☐ **I am retired** (please skip section)

☐ **I do not work for reasons other than my hip condition** (please skip section)

23. How much trouble do you have pushing, pulling, lifting, or carrying heavy objects at work?

☐ **I do not do these actions in my work.**

0------1-------2------3------4------5------6------7------8------9------10

Severe Trouble **No Trouble At All**

24. How much trouble do you have with crouching/squatting?

0------1-------2------3------4------5------6------7------8------9------10

Severe Trouble **No Trouble At All**

25. How concerned are you that your job will make your hip worse?

0------1-------2------3------4------5------6------7------8------9------10

Extremely Concerned **Not Concerned At All**

26. How much trouble do you have at work because of reduced hip mobility?

0------1-------2------3------4------5------6------7------8------9------10

Extreme Difficulty **No Difficulty At All**

IV: SOCIAL, EMOTIONAL AND LIFESTYLE CONCERNS

The following questions ask about social, emotional and lifestyle concerns that you may feel with respect to your **hip** problem. Please think about how you have felt most of the time over the past **month** and answer accordingly.

27. How frustrated are you because of your hip problem?

0------1-------2------3------4------5------6------7------8------9------10

Extremely Frustrated **Not Frustrated At All**

28. How much trouble do you have with sexual activity because of your hip?

☐ This is not relevant to me.

0------1-------2------3------4------5------6------7------8------9------10

Severe Trouble **No Trouble At All**

29. How much of a distraction is your hip problem?

0------1-------2------3------4------5------6------7------8------9------10

Extreme Distraction **No Distraction At All**

30. How difficult is it for you to release tension and stress because of your hip problem?

0------1-------2------3------4------5------6------7------8------9------10

Extremely Difficult **Not Difficult At All**

31. How discouraged are you because of your hip problem?

0------1-------2------3------4------5------6------7------8------9------10

Extremely Discouraged **Not Discouraged At All**

32. How concerned are you about picking up or carrying children because of your hip?

☐ **I do not do this action in my activities.**

0------1-------2------3------4------5------6------7------8------9------10

Extremely Concerned **Not Concerned At All**

33. How much of the time are you aware of the disability in your hip?

0------1-------2------3------4------5------6------7------8------9------10

Constantly Aware **Not Aware At All**

QUESTIONNAIRE COMPLETE!

THANK YOU!

10.13 Trunk Endurance Protocols

10.13.1 Prone Extension Hold

10. PRONE EXTENSION – Time Max
(McGill, 2002 & Konrad et al, 2001)

10.1. Rationale

- Tests capacity of the spine extensors to hold spine alignment against load which is posture specific.
- Significantly related to low back pain for those with low scores to relative average adults.

10.2. Assessment Set Up

Start Position	• Lie face down with feet together & ASIS on edge of box • Tester or partner sits across lower legs below the knee to support athlete • Use a mat for comfort if necessary • Fold arms across the chest maintain erect posture • Start the clock once arms are across the chest • Neck in neutral position (nose pointing to floor) • The trunk is parallel to the floor
Range of Movement	• N/A
Assessment Rules	• Shoulders remain in line with hips • Neutral to slightly extended back position (not hyperextension)
Gross Movement Deviations	• Significant drop of shoulders below hips • Significant hyperextension of the back

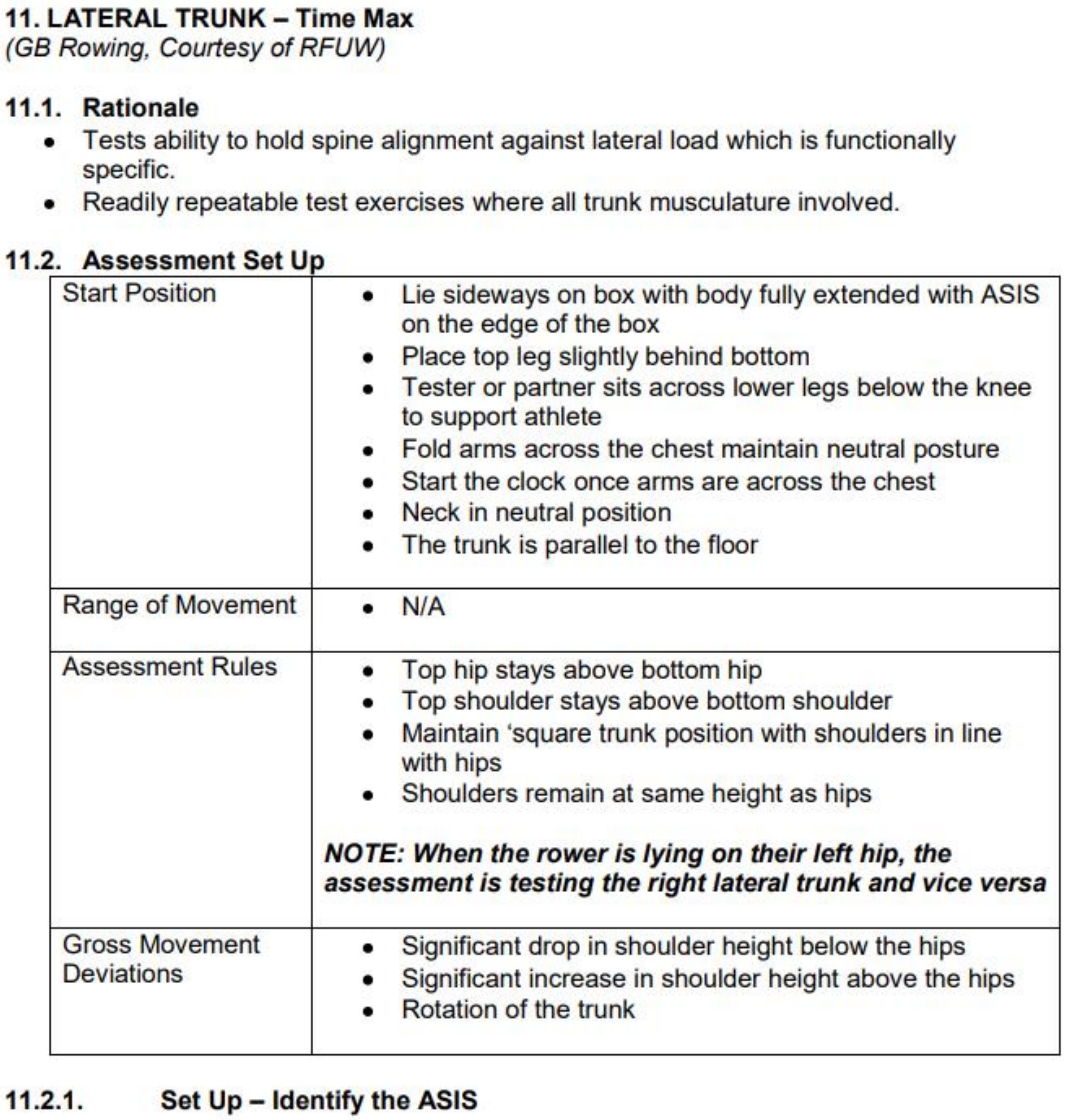
10.2.1. Set Up – Identifying the ASIS

10.2.2. Testing Position – Hip & Shoulder Alignment

10.2.3. Common Fault – Loss of Hip & Shoulder Alignment

10.2.4. Common Fault – Excessive Spinal Extension

10.13.2 Lateral Trunk Endurance Hold



11. LATERAL TRUNK – Time Max
(GB Rowing, Courtesy of RFUW)

11.1. Rationale

- Tests ability to hold spine alignment against lateral load which is functionally specific.
- Readily repeatable test exercises where all trunk musculature involved.

11.2. Assessment Set Up

Start Position	• Lie sideways on box with body fully extended with ASIS on the edge of the box • Place top leg slightly behind bottom • Tester or partner sits across lower legs below the knee to support athlete • Fold arms across the chest maintain neutral posture • Start the clock once arms are across the chest • Neck in neutral position • The trunk is parallel to the floor
Range of Movement	• N/A
Assessment Rules	• Top hip stays above bottom hip • Top shoulder stays above bottom shoulder • Maintain 'square trunk position with shoulders in line with hips • Shoulders remain at same height as hips ***NOTE: When the rower is lying on their left hip, the assessment is testing the right lateral trunk and vice versa***
Gross Movement Deviations	• Significant drop in shoulder height below the hips • Significant increase in shoulder height above the hips • Rotation of the trunk

11.2.1. Set Up – Identify the ASIS

11.2.2. Testing Position – Hip & Shoulder Alignment

11.2.3. Common Fault – Shoulders Drop Below Hip Height

11.2.4. Common Fault – Shoulders Higher than Hips

11.2.5. Common Fault – Torso Rotation