The outcome from anterior cruciate ligament reconstruction in an adult male population from United Arab of Emirates

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Timeline

The PhD thesis started 1/01/2016; The ethical approval from 2 separate organizations, including 1. Al Ahli football club and 2. Up and Running Integrated Sports Medicine Clinic in Dubai were approved. Considering a populations' activity level, they are a male professional and amateur players. A type of participants activity is football, volleyball, handball, basketball, skydivers, and cyclist.

Ethical Approval

The ethical approval issued by Al Ahli Sports Club on 8/2/2016 and Up and Running Clinic on 15/03/2016. The ethical application HSR161763 by the University of Salford approved on 30 May 2017.

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List of abbreviations

2D	**Two dimensional**
3D	**Three dimensional**
6THD	**Six metre timed hop distance**
ACL-RSI	**Anterior cruciate ligament returns to sport after injury questionnaire**
AUC	**Area under the curve**
BPTB	**Bone-patellar-tendon bone graft**
CHD	**Crossover hop distance**
CI	**Confidence interval**
COD	**Change of direction**
CS	**Composite reach distance score**
EMG	**Electromyography**
FPPA	**Frontal plane projection angle**
FPT	**Functional performance test**
FR	**Functional recovery**
GRS	**Global rating score**
GET	**Gravity effected torque**
APT	**Angle peak torque**
IPAQ	**International physical activity questionnaire**
LBP	**Lower back pain**
LCL	**Lateral collateral ligament of the knee**
LESS	**Landing error scoring system**
LSI%	**Limb symmetry index (mean injured/mean non-injured) x100**
MCL	**Medial collateral ligament**
MCID	**Minimal clinical importance differences**
MVIC	**Maximum voluntary isometric contraction**
NRTS	**Non-return to sport**
OA	**Osteoarthritis**

PCL	**Posterior cruciate ligament**
PFPJ	**Patellofemoral pain joint**
PFPS	**Patellofemoral pain syndrome**
PL	**Posterior lateral reach distance**
PM	**Posterior medial reach distance**
PROs	**Patient report outcomes**
QASLS	**Qualitative analysis of single leg squat**
QOL	**Quality of life**
ROC	**Receiver operating characteristics**
SHD	**Side hop distance**
SL	**Single leg**
SLHD	**Single leg hop for distance**
SLL	**Single leg landing**
SLS	**Single Leg Squat**
SS	**Sample Size**
TF	**Treatment failure**
THD	**Triple hop for distance**
TSK	**Tampa Scale of Kinesiophobia**
vGRF	**Vertical ground reaction forces**
YBT	**Y anterior reach balance test**

Abstract

In sports physiotherapy, outcome measurements are used to identify the athlete's ability to tolerate the physical demands inherent in sports specific movement and prevent re-injury or identify readiness to return to competition. There are limited studies utilising multiple tests for the anterior cruciate ligament deficient knee (ACLD) and anterior cruciate ligament reconstruction (ACLR) at three and six months postoperatively especially on an adult male population from the United Arab of Emirates (UAE). Further, there were no studies that examined the relative and absolute reliability for these outcome measures in ACLR patients at three and six months post-operation. The outcome measures utilised in the current study for the ACLD and ACLR at three and six months postoperatively include two subjective questionnaires (KOOS and TSK), Y balance test, 2-dimensional frontal plane projection angle (FPPA) during a single leg squat (SLS) and single leg hop for distance (SLHD), Qualitative analysis of single leg squat (QASLS) during SLS and SLHD and isokinetic knee strength test, these were chosen to provide a wide variety of measurement domains in order to understand the patients performance. Though these outcome measures were reported on for the ACLR patients, the main aim of the current study was to establish relative and absolute reliability following ACLR at three and six months postoperatively. The similar consistency of performance (high ICCs and low SEM values) was achieved during YBT and 2D FPPA during SLHD and SLS in the ACLR patients at three and six months postoperatively. Whereas, the poorer consistency of performance was seen in the isokinetic knee strength test, QASLS during SLSH, KOOS and TSK for the ACLR patients at three months in terms of the ICCs and SEM values compared to six months. The consistency of performance of the isokinetic knee strength, QASLS during SLHD, and TSK improved from three to six months in the ACLR patients. Clinicians need to be aware of the inconsistencies of performance in ACLR patients at three and six months when making decisions regarding progression and RTS, as this could affect the ability of these measures to sensitively assess real change.

Chapter 1

Introduction

Anterior Cruciate Ligament (ACL) injury incidence have risen across all age groups over the last 15-20 years, Abrams et al. (2020) reported increases in the 20–30-year-old age group from 19/100000 in 2005 to 77/100000 in 2015 and 14 to 44/100000 in the 30-40-year-old age group. At the same time, increasing research has become available showing the consequences of ACL injury and its subsequent surgical or conservative (non-surgical) management, with the outcomes being reported as poor with an elevated lifetime risk of developing significant knee osteoarthritis and the requirement for this condition to be managed with total knee replacement (Suter et al. 2017).

Although there are now a growing number of prospective studies which have shown no difference in outcome whether a patient is managed surgically or non-surgically (Frobell et a. 2013; Meuffels et al. 2009; Roemer et al. 2021) athletes who wish to resume high levels of activities after ACL injury are often advised to undergo surgical reconstruction (Marx, Jones, Angel, Wickiewicz and Warren 2003; Seil, Mouton and Lion, 2016). ACL reconstruction (ACLR) aims to stabilize ACL-deficient (ACLD) knee and to prevent future injuries to other knee structures, including meniscus and articular cartilage, which could increase the risk of post-traumatic osteoarthritis (PTOA) (Qiestad et al., 2010; Ardern et al., 2016). It is also suggested by Renstrom (2013) that ACLR is necessary for high level athletes and recreational populations who wish to participate in jumping, pivoting and change of direction sports. Ardern et al., (2011, 2014) suggested that ACLR surgery can provide excellent clinical outcomes and allows around two-thirds of athletes return to sport. The non-surgical (rehabilitation only) approach has been reported to be a viable alternative to ACLR surgery even for professional athletes with high demands on their knee function (Moknes, Risberg, 2009; Frobell et al., 2013 and Grindem et al., 2016). This indicates the significant role appropriate rehabilitation is going to play in outcome regardless of whether the patients does or does not undergo surgery, despite this little consensus exists as to what constitutes an appropriate rehabilitation programme either following surgery or to manage an ACL deficient patient.

In order to develop optimal rehabilitation approaches, there needs to be clarity on both the patient's physical requirements to return to full function (sport, work, etc), that is the end goal and approaches which could mitigate the risk of a poor knee health outcome that results in further damage to the knee. To achieve both goals a rehabilitation programme must be composed of the appropriate training interventions to develop the physical qualities required to deliver these goals. As the goal of the rehabilitation intervention is to develop specific physical qualities, it would be logical that the outcome of both individual elements (specific physical quality goals) and overall programme is measured using appropriate modes of assessment to check these qualities have actually been developed. Unfortunately, currently outcome measures only appear to be used around 50% of the time following ACL surgery (Burgi et al. 2019) and even when an outcome measure is used it is typical a clinical measure such as knee laxity, not a measure of the patient's performance.

Alongside the minimal use performance related outcome measures, the measures themselves are rarely used during the rehabilitation intervention and tend to only to be used prior to "return to sport" or other physical activity. This means the progress of the patient during rehabilitation is not always being assessed until the end stage, so any deficits are not being addressed, making the process inefficient. Furthermore, the measures used may lack validity (internal and external) and reliability, making interpretation of meaning of the data itself difficult. There would appear to be a need to fully assess outcome measures and identify those which are most appropriate to meet the requirements of the specific goals of the individual elements of a rehabilitation programme, so the patient's progress within those individual elements can be clearly defined.

Outcome measurements are used to identify an athlete's ability to tolerate physical demands inherent in sports physical activity and so could help prevent recurrent injury following RTS (Clark, 2001). Regarding the knee, outcome measures used following ACL injury (and reconstruction) include clinical (joint range of motion, joint laxity, swelling), strength, functional performance tests (FPT), and subjective questionnaires. Strength and FPT measures are frequently utilised with ACL deficient (ACL-D) and ACLR athletes to due to their ability to objectively quantify isolated or combined parameters of knee function at the stage of returning to sport (end of rehabilitation) (Borsa et al., 1998; Miller and Carr, 1993). The more traditional clinical outcome measures, such as knee joint laxity, isokinetic muscle strength have only demonstrated weak to moderate relationships to functional tasks in ACLD and ACLR patients, and un-injured athletes (Eastlack et al., 1999; Greenberger and Paterno, 1995; Lephart et al., 1992; Noyes et al., 1991; Petschnig et al., 1998; Sekiya et al., 1998) so provide a poor indicator of the patient's ability to return to sporting performance. Furthermore, the relevance of some of the FPT's in isolation to identify knee performance has also been questioned (Kotsifaki et al. 2021; Ohji et al. 2021) So, it would appear that the use of single or limited number of outcome measures may lack the external/ecological validity to fully understand all of the physical qualities and performance elements required for a patient to optimally and safely return to sport or high-level activity. Furthermore, not only might these outcome measures lack external validity, but they also might lack internal validity through the absence of data reporting test reliability. Without reliability data specific to the population being tested meaningful changes in the measures undertaken cannot be established, so changes in performance measures could have occurred by chance not due to the training interventions undertaken.

When returning to the sport, there appears to be an unacceptably high reinjury rate of either the previously non injured contralateral ACL or rupturing of the ACL reconstruction. Webster et al. (2016), in their cohort study, reported a reinjury rate of 28.3% in under 21-year-olds, and Della Villa et al. (2021) found a reinjury rate of 17.8 % in UEFA champions league footballers. This would appear to indicate a potential failure in the current measures of assessing readiness to return to sport and high-level activities.

Currently, outcome from ACL injury whether managed surgically or not is uncertain, with a poor rate of return to previous levels of activity, high reinjury rates and an elevated risk of significant comorbidity in the knee, some of these factors could be correct through an optimised rehabilitation programme. Prior to the development of rehabilitation programme clear goals must be defined and for their impact to be maximised they must be measured in a reliable and valid manner.

The overarching aim of this thesis is to improve the understanding as to why the outcomes from ACLR are poor. In order to achieve this aim this aim the following nine objectives are examined, which explore elements of reliability and validity of outcome measures used or which could potentially be used to understand the ACLR patient's performance across multiple domains:

1. To discover which study/studies have utilised multiple measurement outcome tools (KOOS, TSK, YBT, 2D FPPA during SLS, and SLHD, and isokinetic knee strength) for ACLD knee and following ACLR at three and six months and their findings (chapter 2). Because the use of single (or limited) outcome measurement tools, especially in the ACLD knee and following ACLR at three months may fail to capture sufficiently comprehensive data to make a truly informed decision before commencing outdoor rehabilitation and return to sport. Therefore, the thesis hypothesised that the poor outcome currently found in the literature might be related to the absence of utilising multiple assessment tools to judge outcome/patient status.

2. To examine if literature exists demonstrating relative and absolute reliability of a number of functional performance tests on ACLR patients at three- and six-months post-surgery (chapter 2). Because the data generated from multiple tools must be meaningful and useful in order to allow the practitioners to utilize the tools with confidence. Therefore, it was hypothesised that a literature search would not discover relative and absolute reliability with the chosen primary outcomes following ACLR at three and six months.

3. To assess the multiple outcome measures for ACLD knee and compare those to a control group of not previously assessed population of Middle Eastern males (chapter 3). The control group was chosen in order to avoid using non-injured leg of the ACLD group as a reference limb because after ACL injury the non-injured limb goes through a detraining effect due to reduced physical activity as a consequence of the injured limb. Therefore, it was hypothesised that the control group perform better from the ACLD group.

4. To compare the result of the multiple tests between ACLR patients at three months to the dominant limb of the control group (injured to non-injured limb; injured to control limb and non-injured to control limb) (chapter 4). The control group was chosen to monitor the

rehabilitation progression after ACLR at three months postoperatively to compare the injured and non-injured limb of the ACLR group to the control group. Therefore, it was hypothesised that the control limb would perform better than both injured and non-injured leg of the ACLR group at three months.

5. To compare the result between ACLR at six months to control limb (injured to non-injured leg; injured to control limb and non-injured to control limb) (chapter 4). The control group was chosen to monitor the rehabilitation progression after ACLR at six months postoperatively to compare the injured and non-injured limb of the ACLR group to the control group. Therefore, it was hypothesised that the control limb would perform better than both injured and non-injured limb of ACLR at six months.

6. To compare the result between the injured limb of ACLR at three months to the injured limb of ACLR at six months (chapter 4). The injured limb of ACLR group at six months was compared to the injured limb of ACLR at three months to monitor the progression of the patient based on the multiple chosen tests. Therefore, it was hypothesised that the injured limb of the ACLR at six months would perform better than the injured limb of three months postoperative ACLR.

7. To establish the relative reliability (ICC (3,1) and 95% confidence interval) and absolute reliability (standard error of measurement) for the multiple tests for the ACLR at three months (chapter 5). Further, to compare the relative and absolute reliability between the control and the ACLR group at three months postoperatively. It was hypothesised that the control group achieve higher relative reliability and lower absolute reliability (SEM scores) compared to the ACLR at three months.

8. To establish relative and absolute reliability for the same tests for the ACLR at six months (chapter 5). Further, to compare the relative and absolute reliability between the control and the ACLR at six months postoperatively. It was hypothesised that the control group achieve higher relative reliability and lower absolute reliability (SEM scores) compared to the ACLR group at six months.

9. To compare the relative and absolute reliability of the same tests between the ACLR at six months to three months (chapter 5). It was hypothesised that the ACLR group at six months achieve higher relative reliability and lower absolute reliability (SEM scores) compared to the ACLR group at three months.

Chapter 2: Literature review

This literature review is composed of two elements first is a brief overview of the literature surrounding the various measurement tools used to assess outcome from ACL reconstruction. The second element is a systematic review assessing specific questions related to the use of outcome measures following ACLR.

Patient Report Outcomes (PROs)

Ardern et al., (2015) has identified ten studies (Ardern, Taylor, Feller and Webster, 2015; Ardern, Taylor, Feller and Webster, 2013; Ardern, Osterberg, Tagesson, Gauffin, Webster and Kvist, 2014; Bohu, Klouche, Lefevre, Webster, Herman, 2014; Kvist, Sporrstedt, and Good, 2005; Langford, Webster, Feller, 2009; Lentz, Zeppieri, George, 2015; Lentz, Zeppieri and Tillman, 2012; Muller, Kruger-Franke, Schmidt, and Rosemeyer, 2014; Tjong, Murnaghan, Nyhof-Young, Harris, 2014; Webster, Feller and Lambros, 2008) that examined the effect of modifiable factors on returning to the pre-injury level after ACLR. Ardern et al., (2015) has identified three factors, including fear of re-injury, psychological readiness to return to sport and subjective assessment of knee function as being critical (refer to the introduction of chapter 2 for TSK details).

Barenius, Forssblad, Engstrom, and Erikson (2013) has defined functional recovery (FR) as a Knee Osteoarthritis Outcome Score (KOOS) above: 90 for pain, 84 for Symptoms, 91 for ADL, 80 for Sport/Rec and 81 for quality of life (QOL) and treatment failure (TF) defined as a KOOS, QOL < 44. Barenius, Forssblad, Engstrom, and Erikson (2013) also reported that 41.4 % of patients who completed KOOS questionnaire two years after ACLR, only 19.7% were functionally recovered two years following ACLR. The use of simple surveys could help clinicians to assess patient's ability return to play by having cutoff values, SEM and SDD to discover real improvement by intervention's or measurement noise following ACLR at seven months and two years. Therefore, one of the purposes of the current study is to establish reliability within and between days of the KOOS subscales for ACLD knee and following ACLR at three and six months to screen a score progression from the pre-operative stage of ACL rupture to ACLR at three and six months (refer to the introduction of chapter 2 for KOOS details).

Functional Performance Tests (FPTs)

Functional performance tests (FPTs) have been utilised in ACL injury and following ACLR in recent years in both sport and clinical practice to provide an outcome measure when evaluating athletes returning to sport (Borsa, 1998; Miller and Carr, 1993; Clark, 2001). FPTs are generally closed chain in nature and therefore closely resemble the joint loading forces and kinematics that could occur functionally and also require minimal space, time, expense and administration (Clark, 2001). A range of FPTs have been assessed in the literature, including hop for distance tests, star excursion balance test (SEBT), anteromedial lunge, step-down, stairs hop, vertical jump, carioca's, agility and sprint tests (Barber, Noyes, Mangine, McCloskey, & Hartman, 1990; Clark, 2001; Delextrat & Cohen, 2008; Goh & Boyle, 1997; Gribble, Hertel, Denegar, & Buckley, 2004; Herrington, Hatcher, Hatcher, & McNicholas, 2009; Loudon, Gajewski, Goist-Foley, & Loudon, 2004; Negrete & Brophy, 2000; Noyes, Barber, & Mangine, 1991; Petschnig, Baron, & Albrecht, 1998; Reid, Birmingham, Stratford, Alcock, & Giffin, 2007; Risberg & Ekeland, 1994; Rudolph, Axe, & Snyder-Mackler, 2000; Semenick, 1990). The vertical jump, carioca's and agility tests require both limbs to work simultaneously to complete the test and therefore do not allow for easy comparison between the injured and uninjured leg. In contrast, single limb tests such as the hop tests, single leg vertical jump, stair hop and SEBT, can utilise the uninjured limb as a comparator for within-subject comparisons, making it relatively easy to quantify the function of the injured leg.

Each of these unilateral (single leg vertical jump, SL hop tests, stairs hop and SEBT) FPTs can detect differences between injured and uninjured limb following ACL injury (Barber et al., 1990; Goh & Boyle, 1997; Risberg & Ekeland, 1994). However, the stair hop test requires a set of stairs, with at least 11 steps, this is not always available in a clinical environment and limits the convenience of this test for use in the field.

Noyes, Barber, and Mangine (1991) developed a set of four hop tests (single leg hop for distance (SLHD), triple hop for distance (THD), crossover hop for distance (CHD), and 6 metres timed hop (6THD) to measure force production, power, distance and force absorption. However, single leg hop tests were noted to have poor sensitivity in 67 patients with ACLD reporting only 50% had abnormal limb symmetry score (Noyes, Barber, and

Mangine, 1991).

In order to compare and evaluate performance between limbs during the hop tests, the limb symmetry index (LSI) is used. Calculation of an LSI involves an injured limb's value divided by the other non-injured limb's value and the result multiplied by 100 to yield a percentage (Barber et al., 1990; Clark, 2001; Risberg et al., 1995). The LSI is useful to clinicians since it can be quickly and easily calculated to give a comparison between limbs. The LSI is generating a single unit (%) potentially indicative of injured limb deficits. However, clinicians should acknowledge three assumptions underlying the application of the LSI. First, the assumption the control (uninjured) limb is `normal' concerning the variables measured within an FPT. Second, the assumption the control limb has not undergone a significant `detraining-effect' secondary to reduced physical activity as a consequence of the injured limb. Third, there is no effect of limb dominance (e.g., `stronger' limb vs `weaker' limb).

Isokinetic knee flexors and extensors strength test

An isokinetic dynamometer is a method commonly used in the assessment of muscle strength, both in research and in clinical practice (Dvir, 2004). In order to be clinically meaningful; the assessment procedure must be reliable and sensitive enough to assess whether a finding indicates impairment and to evaluate outcomes of therapeutic intervention. Preoperative and postoperative quadriceps strength influence functional outcomes after ACL reconstruction, with stronger patients having better results after ACL reconstruction (Eitzen et al., 2009; Hurd et al., 2008; Keays et al., 2003; Lewek et al., 2002; Noyes et al., 1991).

Considering the mode of muscle contraction in the current study, the eccentric muscle action was used because it is capable of producing higher forces and relates to sporting tasks such as deceleration and landing (Komi, 1973 and Rodgers et al., 1974). However, the force differences between eccentric and concentric contractions are velocity dependent (Rodgers et al., 1974; Griffin, 1987; Smidt, 1973). If the velocity of contraction is increased, the maximum eccentric force producible increases and the maximum concentric force decreases but at higher velocities the eccentric effect plateaus (Komi, 1973). For the same velocity, the eccentric strength is greater than the concentric strength (Dvir et al., 1989). Regarding the range of test velocities in isokinetic knee strength testing can start from low to medium (30°/s-60°/s) velocity and can reach as high as 500°/s. However, the use of such a high velocity is not recommended because it places the active muscle in the stretching length poses a severe threat to the integrity of the muscle (Dvir, 1995). The low to medium angular test velocity (60°/s-120°/s) provide useful information regarding muscular performance in order to discover strength deficiency around the knee joint (Dvir 1995).

One significant factor affecting isokinetic measurements is the moment of the gravitational forces of the involved limb and the dynamometer arm (Kellis and Baltzopoulos 1996). Nelson and Duncan (1983) introduced a simple method for gravity correction by measuring the dynamometer moment in a 30° knee flexion from a static position to reduce hamstring tension (Fitzgerland et al., 1991; Westing and Seger, 1989).

Harding, Black, Bruulsema, Maxwell, and Stratford, (1999); Impellizzeri, Bizzini, Rampinini, Cedera, and Maffiuletti, (2008); Pincivero, Lephart, and Karunakara, (1997); Sole, Hamre, Milosvljevi, Bicholson, and Sullivan, (2007) have reported relative and absolute reliability of isokinetic parameters of knee muscles. When selecting clinical and functional performance outcomes measurement, the reliability, validity, and data analysis must acknowledge because the data generated must be meaningful and useful. These issues are critical if an athlete wants to RTS safely, and the risk of re-injury is to minimize. Reliability refers to whether a specific measurement protocol reduces measurement error (i.e. systematic and random error) producing accurate and consistent measurements during repeated measures of the same variable (Atkinson et al., 1998; Greenfield et al., 1998; Krebs 1987; Portney et al., 1993; Rothstein 1993). For the sports injury specialist, `high' measurement reliability is critical if criteria-based return-to-competition decisions potentially result from data generated within objective outcome measures (Clark 2001). The intraclass correlation coefficient (ICC) is the recommended convention for quantifying the reliability of a physical measurement procedure in sports medicine (Denegar & Ball 1993), with an ICC ≥ 0.90 considered indicative of `high' measurement reliability (Portney & Watkins 1993).

Quality assessment of functional performance

Injury to the knee joint complex is one of the most common in sport (Hootman, Dick, & Agel, 2007; Starkey, 2000). In particular, injury to the anterior cruciate ligament (ACL) and patellofemoral joint (PFJ) are responsible for a significant amount of time-loss in sport (Starkey, 2000). A large proportion of ACL injuries in sports occur during non-contact change of direction (COD) manoeuvres (plant-and-cut or pivot actions), which have the propensity to generate high forces and multiplanar knee joint loading (sagittal, frontal and transverse plane moments simultaneously) during the plant foot contact when changing direction (Besier et al., 2001; Kristianslund et al., 2014). To identify high-risk factors for athletes during physical activities, Wilson et al., (2006) and McLean et al., (2005) used 3 dimensional (3D) and 2D motion analysis respectively to quantify abnormal lower limb biomechanics. However, 3D motion analysis is not practical due to the financial, spatial, and temporal cost for the most clinical setting. Therefore, 2D motion analysis techniques are less expensive, portable and easy-to-use overcoming the logistical limitations of 3D motion analysis.

Measuring knee valgus with 2D FPPA and trunk displacement with the qualitative scoring system (QASLS) may improve functional outcome measurement of ACL injury risk factors and monitor a progression during rehabilitation. Almangoush, Herrington, and Jones (2014) reported very good to excellent inter-observer reliability and intra-observer reliability of a qualitative scale of the limb alignment during the SLS test (QASLS) on four healthy subjects. Therefore, one of the aims of this study to establish relative and absolute reliability for 2D FPPA along with QASLS score on ACLD patients and following ACLR on patients at three and six months.

Summary

At the current time outcome from ACLR could be regarded as poor if judged in terms of reinjury rates, return to the same level of sport rates and the numbers of patients who go on to develop secondary issues such as osteoarthritis, without even considering the impacts on health as a result of the potentially decreased activity levels and all this occurs in a predominantly young population. What appears to be apparent is that better decision making based on strong evidence is required relating to the risk of re-injury (presence of modifiable risk factors for injury) and linked to this readiness to return to sporting activities. This decision making is likely to be enhanced if information is drawn from multiple domains of performance and the data has been reliably collected. The first area this thesis will attempt to assess will be this, that is, are ACLR outcomes currently reported across multiple domains of performance or only limited areas and has the reliability of these measures been assessed and reported. These questions will form the basis of the systematic review.

This thesis will then assess multiple outcome measures in an ACLR population not previously reported on, to both compare if these align with outcomes reported in the literature and also see how they change over the time course of the patients pre and post-operative period (pre-operation or ACL deficient, three and six months post-operation). The combination of multiple measures and the potential changing nature of these measures may provide a unique insight into the ACLR patient rehabilitation journey. Finally, regardless of how appropriate and insightful these measures might be, if they are not reliable, that is, subject to large measurement errors then any decisions based upon them could be flawed.

Outcome from anterior cruciate ligament reconstruction in an adult male population; a systematic review

Abstract

Objective. The aim of this chapter was to discover which study/studies utilised multiple measurement outcome (KOOS, TSK, YBT, 2D FPPA during SLS, and SLHD, and isokinetic knee strength) in ACLD patients and in patients following ACLR at three and six months. Also, to discover if any relative and absolute reliability scores on KOOS, TSK, 2D FPPA during SLS, SLHD and isokinetic knee strength following ACLR patients at three and six months had been published.

Methods. A literature search was conducted. Electronic databases used included Medline, PubMed, Cochrane Library, EMBASE, CINAHL, SPORTDiscus, PEDro, and AMED. The inclusion criteria were English language, publication between October 1990 to October 2017, and primary ACL reconstruction with objective and subjective outcomes used. Two authors screened the selected papers for title, abstract, and full text following predefined inclusion and exclusion criteria. A checklist of the Downs and Black assessed the methodological quality of all articles.

Results. A total of twenty-seven papers were included with full text. Different authors used different study designs for functional performance testing which led to different outcomes that could not be compared. All papers used a measurement for quantity of functional performance except one study which used both quantity and quality outcomes. Several functional performance tests and patient reported outcomes were identified in this review.

Conclusion. No comprehensive research has been carried out over the past 27 years to measure the 2D FPPA during SLS and SLHD on ACLD knee and following ACLR at three and six months. The relative and absolute reliability for KOOS, TSK, YBT, isokinetic knee strength with a mode of concentric and eccentric contractions, and 2D FPPA during two tasks (SLS, SLHD) has not established following ACLR at three and six months. A more comprehensive series of tests are suggested to measure both the quantitative and qualitative

aspects of functional performance pre-operatively and following ACL reconstruction and their reliability needs to be established.

Introduction

ACL injury is a common knee injury with significant risk of physical disability from increased risk of second ACL injury (Paterno, Schmitt, Ford, Rauh, Mayer, Haung, and Hewett 2010; Pinczewski, Lyman, Salmon, Russell, Roe, Linklater 2007; Salmon, Refshauge, Russell, Roe, Linklater, Pinczewski 2006). While an ACL reconstruction procedure is the standard of care for individuals who want to return to high- level activities, recent studies indicate these individuals may still have poor outcomes (Laboute, Savalli, Puig, Trouve, Sabot, Monnier, Dubroca 2010; Paterno, Schmitt, Ford, Rauh, Mayer, Haung, and Hewett 2010).

Return to sports rates are relatively low following ACL reconstruction, with 63% resuming the pre-injury level of activity participation and only 44% returning to competitive sport (Ardern, Webster, Taylor &Feller, 2011). Lai, Ardern, Feller and Webster (2018) have indicating that 83% (95% CI 77%-88%) of elite athletes return to sport. Feucht, Cotic, and Saier (2016) stated that a nearly one out of every five elite athletes who undergoes ACLR did not return to sport, which remains below the expectations of the patients undergoing ACLR. The risk of poor outcome may be related to persistent deficits in muscle strength (Risberg, Holm, Tjomsland, Ljunggren, Ekeland 1990), deficits in athletic performance (Myer, Martin, Ford, Paterno, Schmitt, Heidt, Colosimo, Hewett 2012) and altered limb loading strategies during squatting (Neitzel, Kernozek, Davies 2002), jumping and landing activities (Ernst, Saliba, Diduch, Hurwitz, and Ball 2000; Gokeler, Hoff, Arnold, Dijkstra, Postema, and Otten 2010; Oberlander, Bruggemann, Hoher, and Karamanidi 2013; Orishimo, Kremenic, Mullaney, McHugh, and Nicholas 2010; Paterno, Ford, Myer, Heyl, and Hewett 2007; Paterno, Schmitt, Ford, Rauh, Myer, and Hewett 2011) that are consistently noted following return to high-level activity in this population.

Patient Report outcomes (PRO)

There is a growing emphasis on the psychological impact of ACL injury and ACLR, instruments designed to assess constructs such as kinesiophobia which has been defined as the fear of pain and painful re-injury upon physical movement (Kori et al.,1990) are now frequently used. High reliability of the TSK and short version of TSK-11 and cutoff scores have reported by Woby, Roach, Urmston and Watson (2005) on patients with chronic LBP, but this data is lacking in ACL injured patients.

Previous studies (Flanigan et al., 2013; Czuppon et al., 2014; Tjong et al., 2014 and Ardern et al., 2014) reported an association between lower fear and a higher rate of returning to pre-injury activity after ACLR. Patients with elevated kinesiophobia have also demonstrated insufficient and asymmetric quadriceps strength (Lentz et al., 2015 and Paterno et al., 2018), asymmetric hop performance (Paterno et al., 2018), landing mechanics consistent with those at risk for ACL injury (Trigsted et al., 2018), increased likelihood for second ACL injury (Paterno et al., 2018). It is imperative to consider psychological factors during rehabilitation period at ACL injury and following ACLR populations. Therefore, it is imperative to establish test-retest reliability with measurement error following the ACLR at three and six months, as it is not currently available.

The Knee injury and Osteoarthritis Outcome Score (KOOS) is a valid and reliable outcome measure commonly used in the ACL-injured patients to assess outcomes in knee pain, knee symptoms, knee function in daily activity, knee function in sporting activity, and knee-related quality of life (Roos, Lohmander, Ekdahl, and Beynnon 1998; Roos & Lohmander 2003). High reliability (ICC, SEMs, SDDs) of the KOOS subscales in 57 athletes (male=39, female= 18, age =25.6 years) is reported after 7.6 months ACLR (Salavati, Akhbari, Mohammadi, Mazaheri and Khorami 2011). Therefore, establishing relative and absolute reliability following ACLR at three and six months is imperative for clinicians to allow them to differentiate a clinical meaningful measurement as opposed to noise measurement by intervention (refer to chapter 3 and table 3 in the chapter 2).

Functional Performance Tests (FPTs)

Functional performance testing utilizing qualitative methods evaluates a qualitative proxy for kinetic and kinematics compensation or asymmetry are limited in ACL injury and following ACLR at 3 and 6 months postoperatively. Functional assessments such as the Functional Movement Screen (FMS) (Cook, 2014), Star Excursion Balance Test (SEBT) (Plisky et al., 2006), Y Balance Test (YBT) (Plisky et al., 2009) Landing Error Scoring System (LESS) (Padua et al., 2009) and Qualitative Analysis Single Leg Squat (QASLS)

(Herrington, 2014) all have the ability to identify discrepancies in movement quality but have not been used regularly to assess ACLD and ACLR patients (3 and 6 months postop).

The Y Balance Test (YBT) is a screening tool that measures single leg balance and reach distances in 3 directions: anterior, posterior-medial (PM) and posterior-lateral (PL) and creating a normalized composite reach score (CS), a normalized single direction reach, and/or a single reach direction asymmetry measurement (Plisky et al., 2009). The YBT was modified from SEBT by Plisky et al., (2009) for the intent of improving test repeatability. Both SEBT and YBT have been shown to be predictive of lower extremity injuries in athletes (Butler et al., 2013; Chimera et al., 2016; Gonell et al., 2015; Plisky et al., 2006; Smith et al., 2015). However, the YBT is easier to perform and has higher inter-rater reliability than the SEBT for the normalized reach distances (ICC= 0.99-1.00 (95% Confidence Interval (CI); 0.92-1.0) (Plisky et al., 2009) versus ICC=0.89-0.94 (95%CI: 0.80-0.95) (Gribble, Kelly 2013) and the CS (ICC 0.97-0.99 (95%CI: 0.92-0.99) (Plisky et al., 2009) versus ICC= 0.92 (95%CI: 0.85-0.96) (Gribble, Hertel, 2003). To date, there is no study which has been assessed intra-class and interclass coefficient within day and between days of YBT on ACL injury and following ACLR at three and six months yet, which might start to explain some of the lack of sensitivity. Therefore, further investigation of the reliability of YBT is needed before it can be recommended for use in screening tests.

Single leg hop tests

When considering the reliability of hop tests, Reid et al., (2007) reported absolute reliability ICC= 0.82-0.93 in forty-two patients with ACLR at 4 months postoperatively, along with SEM ranged from 3.04% to 5.59% of leg length, and minimal detectable changes (SDD) were 7.05% to 12.96% of leg length. Studies by Booher, Hench, Worrell, and Stikeleather (1993) and Munro & Herrington (2011) reported between session reliability of hop tests values on healthy subjects. There is no published study reported relative and absolute reliability on patients of any hop tests following ACLR at three- and six-months postoperative phase.

The purpose of assessing SLHD at three months following ACLR in the current study was to measure force absorption and landing quality to compare injured limb to non-injured limbs as a control limb before return to jogging as these are pre-requisites to carry out the task safely (Adams et al., 2012 and Rambaud et al., 2017). Full knee ROM > 95% of the non-injured knee, symmetrical gait pattern, isokinetic knee strength (LSI >70%), SLS >45° knee flexion, and hop test LSI >70% (Rambaud et al., 2017 and Adams et al., 2012) has reported as the criterion before jogging is commenced. If knee valgus observed during SLHD for the ACLR group in the current study, the rehabilitation plan is to correct poor landing technique to strengthen hip musculature to control hip adduction, hip internal rotation, strength of the quadriceps muscle and re-educate neuromuscular stability of the whole kinetic chain. Further, if there is a good quality of landing during SLHD observed for the ACLR group at three months postoperatively (and has met the other criteria), then the subject of the current study could start jogging. Therefore, from the load management point of view, the single-leg hop for distance is a safe test to perform at three months following the ACLR group and helps clinicians examine force absorption and landing quality between the injured limb and non-injured limb prior to progression to more complex high load tasks.

One of the main concerns after ACLR is graft elongation or rupture due to excessive early loading to the injured knee. If the biology of ACLR is the primary concern, then the RTS should delay until eighteen to twenty-four months for ligamentization of ACL graft and reduce recurrent ACL injury (Negalli & Hewett 2016). Claes et al., (2011) stated the ligamentization processes occurs in humans over a much longer duration than that originally observed in animal studies; specifically, humans have a much slower remodelling phase. However, this suggested timeline is not practical in the real world for top athlete who are under high pressure from their clubs and their high expectations to return to sport. In the present study, the close collaboration between an orthopaedic surgeon, physiotherapist and the patient followed for a successful recovery.

When considering the LSI of the single leg hop test for distance, Noyes et al., (1991) reported a value of 85% on ACLD patients. The LSI value increased to 90% in the study by Munro and Herrington (2011) on healthy mixed sex. Furthermore, the LSI value increased to 100% for athletes who participate in pivoting, contact and competitive sports (Thomee et al.,2011). However, the use of contralateral (non-injured) leg as a performance comparison has been questioned, because it may underestimate the exact level of deficit. Regardless of LSI and normalized hop distance to body height, the assessment of quality of landing to assess movement impairment and compensation when patients with an ACL injury and following ACLR landed during single leg hop tasks is going to be important. Furthermore, test-retest reliability between sessions along with measurement error and SDDs are required to discover exact changes.

Quality of motion

The SLS is a movement task regularly used in clinical practice as it simulates common everyday tasks such as stair ascent and descent, as well as sporting activities (Zeller et al., 2003). Three-dimensional motion (3D) analysis systems, is considered the gold standard for kinematic analysis during unilateral and bilateral tasks (Maykut et al., 2015 and McLean et al.,2005). The 3D motion analysis is expensive, is time-consuming, and is currently not widely available in clinical setting comparing to 2D motion system. The 2D motion analysis is reliable, less expensive, requires less space and accurate methods that are time efficient and user friendly are available to facilitate the evaluation of SLS kinematic in the clinical setting (Dingenen et al., 2018). Alahmari et al. (2019) stated a weak correlation between 2D FPPA knee valgus angle and 3D knee valgus angle during forwarding, medial and lateral single-leg landings ranging from r=0.17-0.42 on 34 non-injured physically active individuals. FPPA is not a single movement but rather a combination of movements, which include rotation, so it is unlikely it would ever correlate fully with a single plane of movement. However, Alahmari et al. (2019) found a strong correlation between 2D and 3D hip adduction angle ranging from r=0.70-0.90. The 2D motion analysis may be an appropriate surrogate for the 3D motion for hip adduction during single leg landing. Therefore, Alahmari et al. (2019) indicated that 2D motion analysis could be a valid alternative to 3D when measuring hip adduction angle during single-leg tasks. When considering intra-tester and inter-tester reliability of 2D and 3D FPPA hip adduction, Herrington et al., (2017) reported excellent reliability (ICC 0,97-0.99) for both SLS and single leg landing (SLL) tasks on 15 healthy subjects. Furthermore, within and between day assessment of SLS and SLL showed good to excellent correlations (ICC= 0.72-91). From the inter-tester SEMs perspective point of view, Herrington et al.,

(2017) reported the SEM° ranged from 1.97°-1.99° for both SLS and SLL tasks. Considering within and between day assessment during SLS and SLL angles with FPPA, SEM°= 1.32° -1.93° was reported.

There is no published study measuring inter-class and intra-class reliability within a day and between days and measurement errors values of both 2D FPPA and QASLS on ACLD and ACLR patients that have been reported. Therefore, further investigation of the reliability of 2D FPPA and QASLS are needed before it can be recommended for use in preoperative ACL subjects and ACLR subjects at 3 and 6 months. If the reliability and measurement error of these screening methods can be established, clinicians will be able to use the tests with confidence while also being able to evaluate individual performance more informatively.

Isokinetic strength test

Isokinetic strength testing is a reliable method to measure peak torque of knee extensors and flexors (Che et al., 1996; Impellizzeri et al., 2008; Keskula et al., 1995; Maffiuletti et al., 2007; Sole et al., 2007). Regardless of reporting high reliability of isokinetic knee strength test, unfortunately, recent studies (Gokeler et al., 2016; Toole et al., 2017; Welling et al., 2018) showed that most patients following ACLR failed in passing RTS criteria for quadriceps strength at 6 and 9 months after ACLR. Nagelli and Hewett (2017) reported that muscle strength requires prolonged rehabilitation after ACLR of up to a minimum of 2 years. Furthermore, another modifiable factor could influence quadriceps deficit is the utilisation of bone-patellar-tendon-bone graft (BPTB) in patients after ACLR compared to a hamstring tendon graft (HT) using standardised rehabilitation (Welling et al., 2018). On the other hand, more significant hamstring deficit found in patients after ACLR with HT graft compared to BPTB graft (Hughes et al., 2019). Therefore, relative and absolute reliability of isokinetic knee strength is imperative for clinicians to define whether changes in outcomes measurement (relative peak torque and LSI) at retest can be considered a real alteration or measurement error. Furthermore, when considering RTS criteria apart from the prospective reliability point of view, biological healing and graft type are also should recognised.

The angle of peak torque (APT), peak torque (PT) and gravity effected torque (GET) are essential variables during isokinetic knee extensor and flexors muscles during slow and high angular velocities (Fillyaw et al., 1986). At higher angular velocity with uncorrected gravity, the PT of quadriceps will decrease due to the weight of the limb and antigravity movement of quadriceps. Further, the hamstring PT increases because of the weight of the leg and passive fall through 90 degrees from full knee extension to flexion (Fillyaw et al., 1986). Fillyaw et al., (1989) examined two velocities (60°/s, and 240°/s) on 25 healthy female basketball players, stated increasing isokinetic speed produced a 43% decrease in corrected gravity quadriceps femoris PT. Still, a 46% decrease in corrected gravity hamstring peak torque, resulted in a significant reduction from .54 to .51 in the hamstring to quadriceps femoris ratio. Because limb weight is a constant, unaffected by changes in angular velocity, only a difference in the angle of peak torque could account for different gravity effect torques at the two speeds (60°/s, and 240°/s).

The angle of PT at higher speed (240°/s) decreased in quadriceps by 47° compared to 61° at slow speed (60°/s) because the GET is more significant at a smaller angle (fast speed). However, the angle of hamstring PT increased from 33° at 60°/s to 37° at 240°/ s (Fillyaw et al., 1989). Therefore, correcting gravity is essential to obtain a valid measurement of the peak torque, even more, necessary to determine the relative strength of antagonist inversely affected by gravity.

The first aim of this review is to discover which study/studies utilised multiple measurement outcome tools (KOOS, TSK, YBT, 2D FPPA during SLS, and SLHD, and isokinetic knee strength) for ACLD knee and following ACLR at three and six months for the last 27 years. It was hypothesised that the poor outcome could be occurring because in the literature (and clinical practice) they are not utilising multiple assessment tools, especially in the ACLD knee and following ACLR at three months to capture a comprehensive data before commencing outdoor rehabilitation. Secondly, to examine relative and absolute reliability performed on ACLR patients at three and six months for the last 27 years. It was hypothesised that relative and absolute reliability with the chosen primary outcomes following ACLR at three and six months would not be discovered.

Methodology

Search Strategy

A PRISMA compliant search strategy was used for study selection. The inclusion criteria of studies were as follows: (1) at least one lower extremity/knee functional performance test used as an outcome measurement of the article and patient-reported outcomes, (2) subjects who were pre-operative ACL and post-ACL reconstruction, (3) subjects who utilised bone-patellar tendon-bone autograft and hamstring autograft, (4) studies which were either randomised control trial (RCT), cross-sectional or cohort designs,(4) studies published in English between October 1990 and October 2017 and (5)studies established test re-test reliability following ACLR at three and six months.

The electronic databases used were MEDLINE (MeSH terms), PubMed, Cochrane Library (systematic reviews and controlled trials registers), EMBASE, CINAHL, SPORTDiscus, PEDro (Physiotherapy Evidence database), and AMED (Allied and Complementary Medicine Index). To capture as many relevant references as possible, the reviewers (MK, LH) performed an expanded search; including hand-searching the reference lists of all related articles, texts, and systematic reviews.

A search conducted using the terms, "functional performance outcome measurement of anterior cruciate ligament reconstruction", AND single leg hop tests, AND patient-reported outcomes, AND single leg squat, AND isokinetic knee strength, AND 2-dimensional frontal plane projection angle (FPPA), AND SEBT, AND test re-test reliability (Table 1).

Table 1: search term adopted for a Medline search strategy.

Number	Search Term
1	Functional
2	Performance
3	Outcome
4	Measurement
5	Patient
6	Reported
7	Outcomes
8	Single
9	Leg
10	Hop
11	Test
12	Squat
13	Star
14	Excursion
15	Balance
16	Test
17	Isokinetic
18	Knee
19	Strength
20	Test-retest reliability
21	Anterior cruciate ligament
22	Pre-operatively
23	OR/3-6 months
24	OR/6-12 months
25	OR/1-2-3 years
26	OR/1-4 years
27	OR/5-15 years

Study Identification

Two reviewers (MK, LH) independently reviewed all titles and abstracts that identified from the search strategy. Following the predefined eligibility criteria, the full-text manuscripts for all potentially eligible studies obtained, and then in agreement with the predefined eligibility criteria, the reviewers independently reviewed them a second time.

The following exclusion criteria used: (1) articles not written in English, (2) studies where outcomes have not been measured or unclear (3) and animal studies, and (4) subjects who diagnosed with Posterior cruciate ligament (PCL) rupture, Medial collateral ligament (MCL) grade II and III, Lateral collateral ligament (LCL) grade II, and III, alongside ACL injury.

Downs and Black criteria checklist were used to evaluate the risk for bias (Down and Black 1998). The list consists of 27 items distributed between five subscales (reporting, external validity, bias, confounding, and power), displayed in Table 4. Answers scored were 0 or 1, except for one item in the reporting subscale, which scored 0 to 2 and the single issue of power, which was composed 0 to 5. The maximum total score was, therefore 31.

Two independent investigators graded the methodological quality of the included studies, and the results of the first assessor were presented.

If any disagreements arose regarding the study selection, data extraction, or appraisal score, these were sorted out through discussion between the two reviewers until a consensus was met. Studies were excluded if they achieved a very low methodological score of less than 50% through the CASP system. A total score was calculated by adding up all active items.

Data extraction

Two reviewers (MK and LH) independently extracted based on the following seven categories:

1. Authors and year of publication
2. Aim(s) of the study
3. Primary outcomes (PROs, isokinetic knee strength, SLHD, SLS, 2D FPPA, and SEBT) for ACLD knee and following ACLR.
4. Study population (age, sex, type of sports, level of sports).
5. Methods standardisation (familiarisation, fatigue, warm-up, mode of muscle contractions in isokinetic knee testing, angular velocity during isokinetic knee testing and gravity torque effected)
6. cut off values (LSI, relative strength)
7. ACLR graft type (autograft vs allograft, hamstring or patellar tendon-bone graft).
8. Discover relative and absolute reliability following ACLR at three and six months (Table 3).

Result

Search strategy

A PRISMA compliant search strategy was used, and results are presented in a PRISMA flow diagram (Figure 1) (Moher, Liberati, Tetzlaff, and Altman 2009). As Figure 1 demonstrates, a total of 14194 citations were identified through the search strategy. Twenty-seven papers satisfied the eligibility criteria and were therefore included in the review. This included ten randomized controlled trials and seventeen cohort studies. These were summarized in Table 2. Summaries of studies discovered for relative and absolute reliability for healthy subjects, ACLD knee, and ACLR in Table 3.

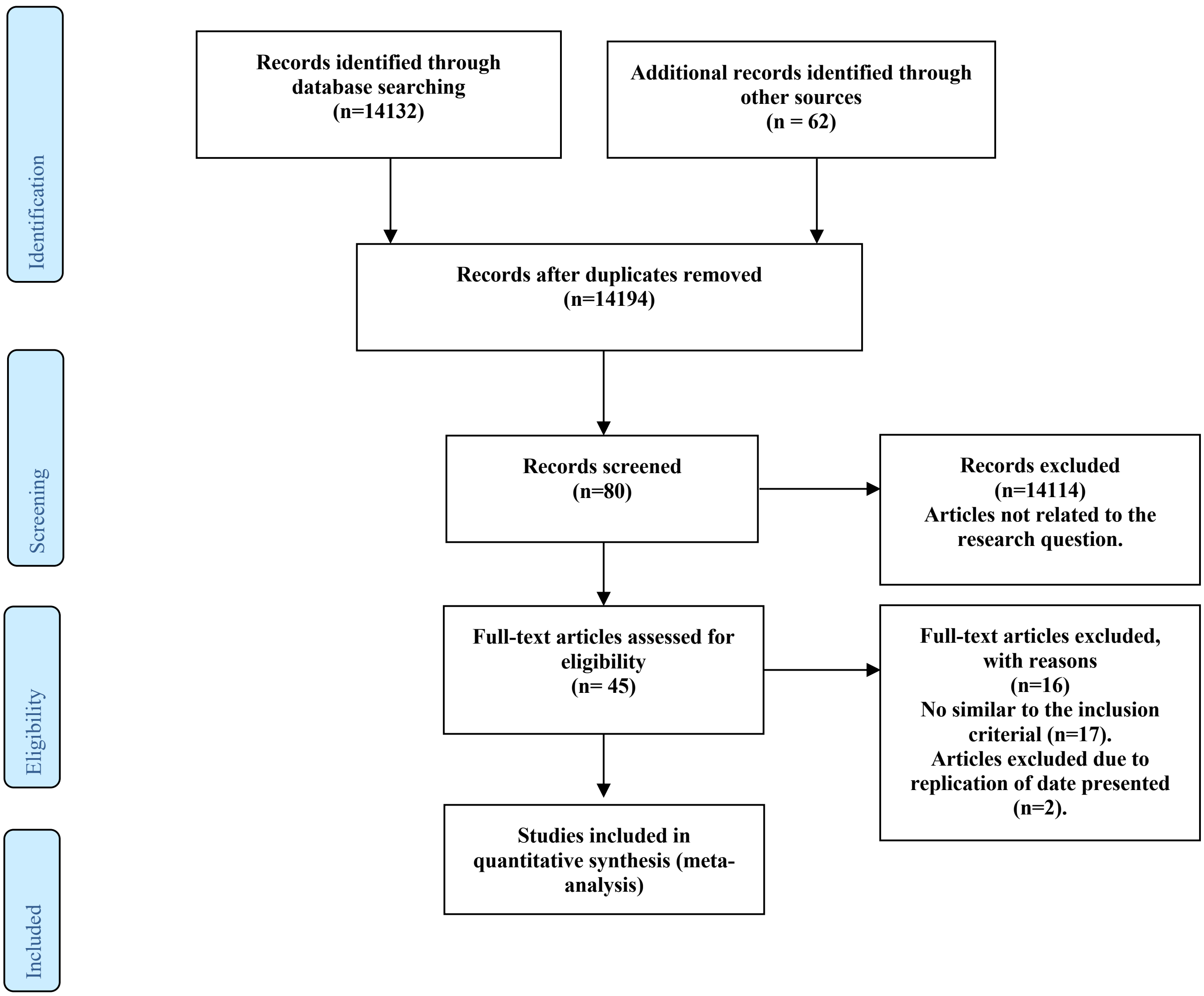

Figure 1. PRISMA flow chart to describe search strategy result.

Table 2: Summary of the studies reviewed

Eligible studies	Focus of study	Study design	Participant details: Sex (F/M), Subject (age)	Isokinetic knee strength test Mode/velocity	Patient reported tools	Functional performance test Qualitative assessment	Qualitative assessment	Results (LSI%)
1. Ageberg et al. 2008	Muscle Strength and Functional Performance in Patients with Anterior Cruciate Ligament Injury Treated with Training and Surgical Reconstruction or Training Only: A Two to Five-Year Follow up	Cohort study	54 (15/39), age (18-35)	N/A	KOOS	Vertical jump (cm) One-leg hop (cm) Side hop (n)	N/A	Surgical group (n=36): Vertical jump=96.4%, One leg hop=99.5%, Side hop=97.9%, Leg press= 98%. Non-surgical group (n=18): Vertical jump=98.8%, One leg hop=98.1%, Side hop=84.2%, Knee extension=94.2%, Knee flexion=97.9, Leg press= 104.6%
2. Benjuya et al. 2000	Isokinetic profile of patient with anterior cruciate ligament tear	RCT	27 males asymptomatic (A), 27 males ACLR involved knee (B), 27 males ACLR sound side (C) age (A= 29, B=31, and C=31)	Concentric/concentric, Velocity 60°/s and 180°/s	N/A	N/A	N/A	N/A
3.Clagg et al 2015	Performance on the Modified Star Excursion Balance Test at the Time of Return to Sport Following Anterior Cruciate Ligament Reconstruction	RCT	ACLR group: 46 female and 20 males with mean age of 17.6 years old. With 26 BPTB autograft, 32 hamstring autograft and 8 allografts. Control group: 32 female and 15 males with mean age of 17 years old.	Mode of concentric contraction of knee extensors and knee flexors at velocity of 180°/s	IKDC	Single leg hop, triple hop, crossover hop distance, time hop, and SEBT.	N/A	Functional outcome with ACLR patients at 6.7 months LSI% THD 95 SLHD 94 CHD 94 Timed hop 97 IKDC 85.8 Modified SEBT LSI% results on ACLR subjects at 6.7 months ANT PM PL BPTB 90.4 63.9 97.5 HT 66.7 100.6 97.5
4.Cardone et al. 2004	Isokinetic assessment of muscle strength following anterior cruciate ligament reconstruction	Cohort study	67 ACLR subjects with mean age (27 years old).	Mode of concentric contractions of knee extensors and knee flexors at velocity of 60, 180, and 240/s at interval of 2-, 4-, and 6-months postoperative periods	N/A	N/A	N/A	knee flexion PT Variables 2 months 4 months 6 months PTN60 120.8 120.2 122.3 PTI60 112.5 90.8 91.9 PTN180 73.2 91.4 92.9 PTI180 75.4 87.8 79.5 PTN240 71 82.8 81.3 PTI240 71.1 75.7 74.2 knee extension PT PTN60 224.4 221.9 222.6 PTI60 150.7 166.5 156.7 PTN180 140.8 151.6 148.1 PTI180 92.9 114.6 122.7 PTN240 123.9 134.7 131.3 PTI240 89 107.9 116.2

5. Frobell et al. 2010	A Randomized Trial of Treatment for Acute Anterior Cruciate Ligament Tears	RCT	121participant divided in two groups (A, B) A= rehabilitation plus early ACLR surgery (F=12, M=50) B= rehabilitation plus delay ACLR surgery (F=20, M=39)	N/A	KOOS, Tegner activity score, SF-36 score	N/A	N/A	KOOS for ACLD knee A B pain 57.3 57.3 symptoms 48.5 47.3 ADL 66.9 69.1 sport 14.6 13.6 QOL 28.3 28.7 KOOS following ACLR at two years pain 87.2 87.7 symptoms 78.7 83 ADL 93.5 94.7 sport 71.8 71.2 QOL 67 63
6. Heijne et al. 2009	Predictive factors for 12-month outcome after anterior cruciate ligament reconstruction	Cohort study	64(F=29, M=35) pre-operative date prior to ACL-reconstruction surgery	Mode of concentric and eccentric contraction of knee extensors and flexors at velocity of 90/s	1.KOOS (only 2 subscales) Function in sports and recreation, and Knee-related quality of life 2. Tegner activity score (TAS)	SLHD	N/A	Post-operative data results (Mean scores) KOOS sport= 76.3 KOOS QOL= 67.1 Single leg hop (Ratio %) = 0.92 TAS= 7
7.Holm et al. 2000	Muscle strength recovery following anterior cruciate ligament reconstruction: A prospective study of 151 patients with a two-year follow-up	Cohort study	151(66/85) mean age (28)	Mode of Concentric/ concentric / speed 60°/sec, and 240°/sec at 6, 12- and 24-months periods.	Cincinnati knee score	THD	N/A	6 months / 12 months / 24 months THD LSI% 92.4 / 95.5 / 92.4 velocity 60/s / 240/s KE6 months 67 / 75.7 KE12 months 82.1 / 83 KE24 months 90 / 89.4 KF6 months 85.6 / 93.2 KF12 months 97.5 / 98.8 KF24 months 96 / 95.6
8. Keays et al. 2003	The relationship between knee strength and functional stability before and after anterior cruciate ligament reconstruction	Cohort study	31 (M=22, and F= 9) aged (19 -38)	Mode of concentric/concentric, velocity of 6Oo/s and 120°/s		Single hop (cm), Triple hop (cm), Shuttle run (s), Sidestep (s), and Carioca (s)	N/A	Isokinetic peak torque and functional test values pre-operation (LSI%) Quadriceps strength(60°/s) = 92.7% Quadriceps strength(12O°/s) = 92.2% Hamstring strength(60°/s) = 98.9% Hamstring strength(12O°/s)= 99% Single hop=82% Triple hop =86.5% Shuttle run =N/A Side step =N/A Carioca =N/A Isokinetic peak torque and functional test values post-operation (LSI%) Quadriceps strength(60°/s)= 88% Quadriceps strength(12O°/s)= 89.7% Hamstring strength(60°/s)= 90 % Hamstring strength(12O°/s)= 90.1% Single hop= 88% Triple hop = 89.6 % Shuttle run =N/A Side step =N/A

9. Liu-Ambrose et al. 2003	The effect of proprioceptive or strength training on the neuromuscular function of the ACL reconstruction knee	RCT	10, age (18-38 years)	Concentric and eccentric/ 45 degrees per seconds	Tegner&Lysholm, Lyshom&Gillquist	Single leg hop distance, and one-legged timed hop	N/A	N/A
10. Moksnes and Risberg et al. 2009	Performance-based functional evaluation of non-operative and operative treatment after anterior cruciate ligament injury	Cohort study	112 (F=56, M=69), Non operated group(n=52), ACLR group (n=50)	N/A	IKDC, KOS-ADLS, Global rating of knee function (VAS 0–100)	Single hop, Triple hop, Triple crossover hop, and timed hop test	N/A	ACLD / Follow up ACLD SLHD 88 / 95.9 THD 87.9 / 95.5 CHD 89.7 / 95.4 Timed hop 93 / 96.2 KOS-ADLS 89.1 / 94.4 GRKE (VAS1-10) 66 / 85.3 IKDC 73.4 / 86.1 Baseline ACLR / Follow up ACLR SLHD 82.7 / 91.8 THD 84.9 / 91.4 CHD 83.6 / 93.5 Timed hop 86.6 / 94.2 KOS-ADLS 83.8 / 92.5 GRKE (VAS1-10) 51.8 / 86 IKDC 63.7 / 87
11. Nyberg et al 2006	Muscle strength and jumping distance during 10 years post ACL reconstruction	Cohort study	63 (24/39) age (19-42)	Isometric, concentric and concentric/ 60, and 180 degrees per seconds	N/A	Single leg hop distance	N/A	N/A
12.Qiestad et al. 2010	Quadriceps Muscle Weakness After Anterior Cruciate Ligament Reconstruction: A Risk Factor for Knee Osteoarthritis?	Cohort study	164(71/94) age (N/A)	Concentric/concentric, velocity (60°/s)	Cincinnati knee score	Triple hop test, stair hop test	N/A	N/A
13.Petschnig et al. 1998	The relationship between isokinetic quadriceps strength test and hop tests for distance and one-legged vertical jump test following anterior cruciate ligament reconstruction	RCT	Group A= 50 healthy males with mean age of 28 years old Group B= 30 ACLR males, mean age 27 years old, 13 weeks postop Group C= 25 ACLR males, mean age of 29 years old, 54 weeks postop	Mode of concentric contraction of knee extensors and knee flexors at velocity of 15/s	Lysholm	Vertical jump, single hop distance, and triple hop distance	N/A	LSI% Group A (N= 50) Vertical jump=95.2, SLHD=97.4, THD= 98.3; Isokinetic =97.1 G r o u p B (N = 30) Vertical jump=46.3, SLHD=73.0, THD =71; Isokinetic =54.7 Group C (N= 25) Vertical jump=74.9, SLHD=88.4, THD=89.5, Isokinetic =87.2

14. Rohman et al 2015	Changes in Involved and Uninvolved Limb Function During Rehabilitation After Anterior Cruciate Ligament Reconstruction	Cohort study	121 (F=59, M=62) mean age (26)	N/A	N/A	Single leg hop distance, single leg squat, triple hop distance, Crossover hop distance, time hop, SEBT	N/A	**Standard functional test at 4 months (SFT1) LSI%** Single leg reach anterolateral= 96.7, Single leg reach anteromedial= 96.1, SLS=88.5, SLHD =78.2, THD=85.9, CHD= 84.5 and Timed hop = 85.3 **Standard functional test at 6 months (SFT1) LSI%** Single leg reach anterolateral= 98.4, Single leg reach anteromedial= 99.0, SLS=96.1, SLHD =90.3, THD=91.6, CHD=92.3, Timed hop = 92.8
15. Risberg et al. 2007	Neuromuscular training versus strength Training During First 6 Months After Anterior Cruciate Ligament Reconstruction:	RCT	74 (F=27, M=47) mean age (28.4)	Mode of concentric contraction at velocity of 60/s, 240/s at preoperative stage, 3, 6, and 12 months postoperative stage	CKS, VASs for pain and functions, SF-36	Single leg hop, triple hop and stair hop		Preoperative n=74 — ST group / NT group SHD 93.7 / 90.1 THD 94.6 / 91.8 CHD 78.4 / 84.8 Flexion TW 60/s 82.9 / 80.6 Flexion TW 240/s 86.8 / 87.6 Extension TW 60/s 79.4 / 79 Extension TW 240/s 83.7 / 84.7 6Months follow-up SHD 81 / 84.9 THD 83.1 / 88.5 CHD 79.8 / 79.8 Flexion TW 60/s 88.3 / 86.3 Flexion TW 240/s 94.7 / 90.8 Extension TW 60/s 67.3 / 79.1 Extension TW 240/s 78 / 79
16. Shaw et al. 2005	Do early quadriceps exercises affect the outcome of ACL reconstruction?	RCT	103 (28/75) Age (18-58 years)	Isometric	CKRS	single hop, triple hop	N/A	Single leg hop for distance LSI 81.8% for no quadriceps exercise group and LSI 83.7% for quadriceps exercise group. Triple hop for distance for no quadriceps exercise group LSI 81.8% and LSI 83.7% for quadriceps exercise group.
17. Tengman et al. 2014	Anterior cruciate ligament injury after more than 20 years. II. Concentric and eccentric knee muscle strength	RCT	ACLR group:33 (M=21, F=12), ACL physiotherapy treatment group:37 (M=23, F=14), Control group:33 (M=21, F=12) mean age (23-28years old)	Mode of contraction concentric and eccentric of knee flexors and knee extensors at velocity of 90/s	N/A	N/A	N/A	**Knee extension relative PT ($N.m.kg^{-1}$) LSI%** ACLR (m=89% and f=87%), ACLPT (m=93% and f=96%), control (m=100% and f=99%) **Knee flexion PT ($N.m.kg^{-1}$) LSI%** ACLR (m=101% and f=106%), ACLPT (m=100% and f=101%), control (m=104% and f=104%) **Knee extension eccentric PT ($N.m.kg^{-1}$) LSI%** ACLR (m=86% and f=89%), ACLPT (m=98% and f=93%), control (m=97% and f=98%) **Knee flexion eccentric PT ($N.m.kg^{-1}$) LSI%** ACLR (m=94% and f=100%), ACLPT (m=88% and f=98%), control (m=100% and f=94%)

18.Tengman et al. 2014	Anterior cruciate ligament injury after more than 20 years: I. Physical activity level and knee function	RCT	ACLR group: 33 (M=21, F=12), ACL physiotherapy treatment group:37 (M=23, F=14), Control group=33 (M=21, F=12)	N/A	TSK, IPAQ, KOOS, Lysholm, TAS	Single leg hop, side hop, and vertical jump	N/A	**No-or-low OA (Kellgren & Lawrence 0–1)** **KOOS** (Pain=88, Symptoms = 86, ADL= 85, Sport/Rec= 92, QOL= 65) SLHD LSI%= 95, Vertical jump LSI%=95, Side hop LSI%= 78 **Moderate-to-high (Kellgren & Lawrence 2–4)** **KOOS(** Pain=81, Symptoms = 72, ADL= 86, Sport/Rec= 56, QOL= 54) SLHD LSI%= 92, Vertical jump LSI%=91, Side hop LSI%= 78
19. Xergia et al. 2013	Asymmetries in Functional Hop Tests, Lower Extremity Kinematics, and Isokinetic Strength Persist 6 to 9 Months Following Anterior Cruciate Ligament Reconstruction	RCT	22 men with mean age of 28.8 years old who undergone ACLR within 6-9 months, 22 health men with mean age of 24.8 years old	Mode of contraction of knee extensors and flexors at velocity of 120°/s, 180°/s, and 300°/s	TAS, and IKDC	Single leg hop, triple hop and crossover hop distance	VICON, hop tests kinematic evaluations (Propulsion, and landing phase.	N/A
20. Beischer et al 2017	Young athletes return too early to knee strenuous sports, without acceptable knee function after anterior cruciate ligament reconstruction	Cohort study	**Included 8 month follow-up ACLR** n=270 (m=131, f=139) **Included 12 month follow up ACLR** No=203 (m=100, f=103) with mean age of 15-30 years	Isometric with 60 degrees of knee extension and 30 degrees of knee flexion, Isokinetic with speed of 90 degrees, with mode of concentric contractions of knee flexor and knee extensor	TAS and KOOS	SLHD, vertical hop, and side hop	N/A	**Isokinetic, hop tests and KOOS result at 8 months following ACLR** Quadriceps LSI%=94, Hamstring LSI%=100, Vertical hop LSI%=88, SLHD LSI%=95, side hop LSI%= 93, KOOS (pain=87, symptoms= 76, sport/Rec=74, QAL=62) **Isokinetic, hop tests and KOOS result at 12 months following ACLR** Quadriceps LSI%=97, Hamstring LSI%=99, Vertical hop LSI%=90, SLHD LSI%=96, side hop LSI%= 97KOOS (pain=89, symptoms= 80, sport/Rec=80, QAL=66)
21. Ebert et al. 2017	Strength and functional symmetry are associated with post-operative rehabilitation in patients following ACLR	Cohort study	111 subjects (m=73, f=38) with mean age of 27.3 years, post-operative ACLR follow up 12.5 months	Isokinetic knee flexor and extensor with speed of 90 degrees, mode of concentric contractions	N/A	Single leg hops for distance, Triple hop for distance, Triple crossover hop for distance, 6-m timed hop.	N/A	**Isokinetic and hop tests result at 12.5 month following ACLR** Quadriceps LSI%=79, Hamstring LSI%=91, SLHD LSI%=86, Timed hop LSI%= 86, THD LSI%= 86, CHD LSI%= 86
22.Gokeler et al. 2017	Development of a test battery to enhance safe return to sports after ACLR	Cohort study	Twenty-eight subjects (m=22, f=6) with mean age of 25.4 years following ACLR at 6.5 months.	Isokinetic knee extensor and knee flexor with velocity of 60/s, 180/s, and 300/s with mode of concentric contractions.	IKDC, ACL-RSI	Single leg hops for distance, triple hop for distance, and side hop.	LESS with 2D motion analysis	**LSI> 90 of patients passed criterion** PTQ60°=39.3%, PTH60°= 60.7%, PTQ180°=46.4%, PTH180°= 53.6%, PTQ300°=42.9%, PTH300°= 78.6%, THD=85.7%, SLHD= 78.6%, side hop= 50%, PT60°= >3.0 (N.m.kg^{-1})= 35.7%, LESS<5=67.9%, IKDC= 85.7, ACL-RSI=75

23. Toole et al. 2017	Young athletes after ACLR with quadriceps strength asymmetry at the time of return to sport demonstrated decreased knee function 1 year later.	Cohort study	76 athletes (74% female with mean age of 17 years old) one year following ACLR.	Isokinetic dynamometer with mode of isometric contraction at 60° of knee flexion	IKDC, and KOOS	Single leg hop for distance, Triple hop for distance, Triple crossover hop for distance, 6-m timed hop,	N/A	LSI>90 LSI<85 THD 101 98 SLHD 100 98 CHD 100 98 Timed hop 101 100 KOOS-P 96 92 KOOS-S 92 87 KOOS-ADL 98 97 KOOS-sport 93 86 KOOS-QOL 86 80 IKDC 94 88
24. Nawasreh et al. 2017	Functional performance 6 months after ACL reconstruction can predict return to participation in the same pre-injury activity level 12 and 24 months after surgery.	Cohort study	95 patient after ACLR at 6 months, Pass(=48), Fail(n=47), 80 patient after ACLR at 12 months Pass(n=37), Fail(n=43), 28 patients after ACLR at 24 months Pass(n=32) Fail(=28)	MVIC with Kin-Com	KOS-ADLS, GRS	Single leg hop for distance, Triple hop for distance, Triple crossover hop for distance, 6-m timed hop,	N/A	Participants' data and RTS criteria variables of the PASS and FAIL groups at 6 months after ACLR LSI% Pass Fail SHD 97.2 92.8 THD 97.3 89.1 CHD 97.9 93.9 Timed hop 97.2 92.8 KOOS-ADLS 97.3 96 GRS 95.3 87.4 Quadriceps 103.3 91.7
25. Hannon et al. 2017	Do muscle strength deficits of the Uninvolved hip and knee exist in the young athletes before ACL reconstruction	Cohort study	64 athletes with 31 ACL injured with mean age of 15.6 years and 33 control group with mean age of 14.9.	Isokinetic knee flexor and knee extensor with mode of concentric contraction at velocity of 60°/s, Handheld dynamometer for isometric testing of hip muscles (extension, rotation and abduction.	N/A	N/A	N/A	Relative peak torque ACL control PTQ60° /s 1.46 1.96 PTH60°/s 0.955 1.01
26. Ithurburn et al. 2017	Young athletes after ACL reconstruction with single leg landing asymmetries at the time of return to sport demonstrate decreased knee function 2 years late.	Cohort study	48 athletes (77% female with mean of age 17.6 years old at the stage of RTS and 2 years later.	N/A	IKDC, and KOOS	Single leg hops for distance, Triple hop for distance, Triple crossover hop for distance, 6-m timed hop,	3 D motion analysis of knee flexion excursion, peak internal knee extension moment and peak trunk flexion	N/A
27. Nawasreh et al. 2017	Do patients failing return to activity criteria at 6 months after ACL reconstruction continue demonstrating deficits at 2 years.	Cohort study	95 patients in 6 months follow up testing with Pass(n=48) and Fail (n=47); 80 patients in 12 months follow up testing with Pass(n=42) and Fail(n=38); 60 patients with 24 months follow up testing, Pass (n=33), and Fail(n=27).	Kin Com with MVIC with 90 ° of knee flexion.	KOS-ADLS, GRS	Single leg hops for distance, Triple hop for distance, Triple crossover hop for distance, 6-m timed hop,	N/A	Participants' data and RTS criteria variables of the PASS and FAIL groups at 6 months after ACLR LSI% Pass Fail SHD 97.2 92.8 THD 97.3 89.1 CHD 97.9 93.9 Timed hop 97.2 92.8 KOOS-ADLS 97.3 96 GRS 95.3 87.4 Quadriceps 103.3 91.7

Table 4: Downs and black checklist

Criteria	1.Ageberg et al. 2008	2.Benjuya et al. 2000	3.Clagg et al. 2015	4.Cardone et al. 2004	5.Frobell et al. 2010	7.Holm et al. 2000	8.Keays et al 2003	9.Liu-Ambrose et al 2003	10.Moksnes and Risberg et al. 2009
1.	+	+	+	+	+	+	+	+	+
2.	+	+	+	+	+	+	+	-	+
3.	+	+	+	-	+	+	+	+	+
4.	+	+	+	+	+	+	+	+	+
5.	+	+	+	-	+	+	-	-	-
6.	+	+	+	+	+	+	+	+	+
7.	+	+	+	+	+	+	+	-	+
8.	+	-	+	-	+	-	-	-	-
9.	+	+	+	-	+	+	-	+	+
10	+	+	+	+	+	+	+	+	+
11	-	+	-	-	-	-	-	+	+
12	-	+		-	-	-	-	-	-
13	-	-	-	-	+	+	-	-	-
14	-	-	-	-	+	-	-	-	-
15	-	-	-	-	+	-	-	-	-
16	-	-	-	-	-	-	+	+	-
17	+	+	+	+	+	+	+	+	+
18	+	-	+	+	+	-	+	-	+
19	+	+	+	+	+	+	+	+	+
20	+	+	+	-	+	-	+	-	+
21	-	-	-	-	-	-	-	-	-
22	+	+	+	-	+	+	+	+	+
23	-	+	+	-	+	-	-	+	+
24	-	-	-	-	-	-	-	-	-
25	-	-	-	-	-	-	+	-	-
26	+	+	+	-	+	+	-	+	+
27	+	-	-	-	-	+	-	-	-
Score	17	17	17	9	20	15	14	12	16

Table 4: Continued

Criteria	11.Nyberg et al. 2006	12. Qiestad et al. 2010	13.Petschnig et al. 1998	14.Rohman et al. 2015	15.Risberg et al. 2007	16.Shaw et al 2005	17.Tengman et al. 2014	18.Tengman et al. 2014	19.Xergia et al. 2013	20.Ebert et al. 2017
1.	+	+	+	+	+	+	+	+	+	+
2.	+	+	+	+	+	+	+	+	+	+
3.	-	+	+	+	+	+	+	+	-	-
4.	+	+	+	+	+	+	+	+	+	+
5.	-	+	-	-	+	+	+	+	-	-
6.	-	+	+	+	+	-	+	+	-	+
7.	-	+	+	+	+	-	+	+	+	+
8.	-	-	-	-	-	-	-	-	-	+
9.	-	+	-	-	-	-	+	+	-	-
10	+	+	+	+	+	+	+	+	+	+
11	-	-	-	-	+	+	+	+	-	+
12	-	-	-	-	-	+	-	-	-	-
13	+	+	-	-	+	-	+	-	-	-
14	-	-	-	-	+	+	-	-	-	-
15	-	-	-	-	-	+	-	-	-	-
16	-	-	-	-	-	+	-	-	-	-
17	+	+	+	+	+	+	+	+	-	-
18	+	+	+	+	+	+	+	+	-	+
19	-	+	+	+	+	-	+	+	-	+
20	-	-	+	-	+	-	+	+	+	-
21	-	-	-	+	-	-	-	-	-	-
22	+	+	+	-	+	-	+	+	-	-
23	-	-	+	-	+	+	+	+	+	-
24	-	-	-	-	+	-	-	-	-	-
25	-	-	-	-	-	-	-	-	-	-
26	-	+	+	+	-	-	+	+	-	+
27	-	-	-	-	+	-	-	-	-	+
Score	7	15	14	11	20	14	18	18	7	12

Table 4: Continued

Criteria	21.Gokeler et al. 2016	22.Beischer et al. 2017	23.Nawaresh et al. 2016	24.Toole et al. 2017	25. Hanon et al. 2017	26.Nawaresh et al. 2017	27.Ithurburn et al. 2017
1.	+	+	+	+	+	+	+
2.	+	+	+	+	+	+	+
3.	+	-	+	+	+	+	+
4.	+	+	+	+	+	+	-
5.	+	-	-	-	-	-	+
6.	+	+	+	-	+	_	+
7.	-	+	+	+	+	+	+
8.	+	-	+	-	-	-	-
9.	+	-	-	+	+	+	+
10	-	+	+	+	+	+	-
11	+	-	+	+	+	+	-
12	-	-	-	-	-	-	-
13	+	-	-	-	+	-	-
14	-	-	-	-	-	-	-
15	-	-	-	-	-	-	-
16	-	-	-	-	-	-	+
17	-	+	+	+	+	+	+
18	+	-	+	+	+	-	-
19	+	+	-	-	+	-	+
20	+	-	+	+	+	-	+
21	-	-	+	-	-	-	-
22	-	-	-	-	-	-	-
23	-	-	-	-	-	-	-
24	-	-	+	+	-	-	-
25	-	+	-	-	-	-	-
26	+	+	+	-	-	-	-
27	+	+	+	+	+	+	+
Score	15	11	16	13	15	10	12

Table 3. Summaries of studies for relative and absolute reliability among healthy, ACLD knee and ACLR subjects

Author	Healthy subject	ACLR subjects	Outcome measures	Test re-test reliability
Woby et al. 2005	Yes	No	TSK	ICC= 0.83 SEM= 3.16
Salavati et al. (2011)	No	57 (m=39 and f=18) mean time 7.6 months	KOOS	KOOS (0.75-0.93), and SEM (2.1-3.1)
Reid et al. 2007	No	42 (f=19 and m=23) 4 months	SLHD, THD, CHD and timed hop distance	ICC= (0.82-0.93) and SEM= (3.4%-5.59%)
Gustavsson et al. 2006	15(m=9 and f=6)	30 ACLD (m=18 and f=12) and 35 (m=25 and f=10) ACLR at six months	Five single hop tests (vertical hop, hop for distance, drop jump followed by a double hop for distance, square hop and side hop	ICC= (0.85-0.97)
Plisky et al. 2009	15 males	No	Y balance test	ICC= 0.89 SEM (cm)= 5.84
Dobija et al. 2019	33	33 ACLD	SEBT	SEBT ICC= (0.88-0.96) SEM= 2.70-4.03cm
Munro &Herrington, 2010	22 (m=11 and f=11)	No	YBT	ICC= 0.84- 0.92 SEM%= 2.21-2.94%
Impellizzeri et al. 2008	18	No	Isokinetic knee flexor and extensor with a mode of concentric and eccentric contraction with velocity of 60°/s, 120°/s and 180°/s	ICC= 0.90-0.98, SEM= 4.3%-7.7%
Sole et al. 2007	18(m=11 and f=7)	No	Isokinetic knee flexor and extensor with mode of concentric and eccentric contractions with velocity 60°/s	ICC>0.90, SEM=5%-10%
Munro et al. 2012	20 (m=10 and f=10)	No	2D FPPA during SLS, drop jump and single leg landing from a 28cm box	ICC=0.59-0.88 within day, ICC=0.72-0.91 between days SEM= 2.72°-3.01°

Strength measurement

Twenty-one studies reported results of isokinetic knee strength measurement with varying angular velocities (45°/s, 60°/s, 90°/s, 120°/s, 180°/s, 300°/s), and mode of contractions (isometric, concentric/concentric and concentric/eccentric), specific measurement parameter values (absolute peak torque (N.m), relative peak torque ($N.m.kg^{-1}$), work (joule) and a mixed result of sex (Benjuya et al., 2000; Clagg et al., 2015; Cardone et al., 2004; Heijne et al., 2009; Holm et al., 2000; Keays et al., 2003; Liu-Ambrose et al., 2003; Nyberg et al., 2006; Qiestad et al., 2010; Petschnig et al., 1998; Risberg et al., 2007; Shaw et al., 2005; Tengman et al., 2014; Xergia et al., 2013; Beischer et al., 2017; Ebert et al., 2017; Nawasreh et al., 2017; Hannon et al., 2017; Nawasreh et al., 2017; Toole et al. 2017; Gokeler et al., 2017) (Table 2), because of the varying parameters and their impact on peak torque etc direct comparison is difficult.

Three out of twenty-one studies reported knee strength measurement with a mode of concentric and eccentric contractions of knee flexors and extensor who had undergone ACLR surgeries with autograft of both BPTB and hamstring alongside different angular velocity (90°/s,45°/s) (Heijne et al., 2009; Liu-Ambrose et al., 2003; Tengman et al., 2014). Studies by Impellizzeri et al., (2008) and Sole et al. (2007) reported relative and absolute reliability with the velocity (60°/s,120°/s and 180°/s) on healthy subjects. Still, no studies examined the relative and absolute reliability on ACLR at three and six months (Table 3).

Patient reported outcomes

Nineteen studies (Ageberg et al., 2008; Clagg et al.,2015; Frobell et al., 2010; Heijne et al.,2009; Holm et al., 2000; Liu-Ambrose et al., 2003; Moksnes and Risberg 2009; Qiestad et al., 2010; Petschnig et al., 1998; Risberg et al., 2007; Shaw et al., 2005; Tengman et al., 2014; Xergia et al., 2013; Beischer et al., 2017; Nawasreh et al., 2017; Nawasreh et al., 2017; Toole et al., 2017; Ithurburn et al., 2017; Gokeler et al. 2017) reported questionnaires presented in table 2. Seven studies used KOOS score (Ageberg et al., 2008; Frobell et al., 2010; Heijne et al., 2009; Tengman et al., 2014; Beischer et al., 2017; Ithurburn et al 2017; Toole et al. 2017) (Table 2).

Six papers assessed the international knee documentation committee (IKDC) (Clagg et al., 2015; Moksnes and Risberg 2009; Xergia et al., 2013; Toole et al., 2017; Ithurburn et al., 2017; Gokeler et al. 2017), the Lysholm score (Liu-Ambrose et al., 2003; Petschnig et al., 1998; Tengman et al. 2014), and the Cincinnati knee score (Holm et al., 2000; Risberg et al., 2007; Shaw et al., 2005). Six studies used Tegner activity score (TAS) (Frobell et al., 2010; Heijne et al., 2009; Liu-Ambrose et al., 2003; Tengman et al., 2014; Xergia et al., 2013; Beischer et al. 2017).

Two papers reported short-form survey (SF-36) (Frobell et al., 2010; Risberg et al. 2007), and three studies per each score evaluated the global rating scale (Moksnes and Risberg 2009; Nawasreh et al., 2017; Nawasreh et al. 2017), the KOS-ADLS questionnaire (Moksnes and Risberg 2009; Nawasreh et al., 2017; Nawasreh et al. 2017). A study reported a Tampa scale for kinesophobia (TSK) (Tengman et al. 2014), and the international physical activity questionnaire (IPAQ) (Tengman et al. 2014). The use of a multitude of different questionnaires makes all but superficial comparisons difficult.

Single leg hop for distance

The single leg hop for distance was assessed in nineteen studies (Ageberg et al., 2008;Clagg et al., 2015; Keays et al., 2003; Liu-Ambrose et al 2003; Moksnes and Risberg 2009; Petschnig et al., 1998; Qiestad et al., 2010; Rohman et al., 2015; Risberg et al., 2007; Shaw et al., 2005; Xergia et al., 2013; Beischer et al., 2017; Nawasreh et al., 2017; Ebert et al.,2017; Nayberg et al.,2006; Nawasreh et al., 2017; Toole et al., 2017; Ithurburn et al., 2017; Gokeler et al., 2017) of the papers included. Triple hop test for distance was evaluated in sixteen papers (Clagg et al., 2015; Keays et al., 2003; Holm et al., 2000; Moksnes and Risberg 2009; Petschnig et al., 1998; Qiestad et al., 2010; Rohman et al., 2015; Risberg et al., 2007; Shaw et al., 2005; Xergia et al., 2013; Nawasreh et al., 2017; Toole et al., 2017; Ithurburn et al., 2017;Gokeler et al., 2017; Ebert et al., 2017; Nawasreh et al. 2017).Ten studies described a 6-meter timed hop test for speed (Clagg et al. 2015; Liu-Ambrose et al. 2003; Moksnes and Risberg 2009; Rohman et al. 2015; Nawasreh et al. 2017; Toole et al. 2017; Ithurburn et al. 2017; Gokeler et al. 2017; Ebert et al. 2017; Nawasreh, 2016). Nine studies have reported a crossover hop for distance (Clagg et al. 2015; Moksnes and Risberg 2009; Rohman et al., 2015; Xergia et al., 2013; Nawasreh et al., 2017; Toole et al., 2017; Ithurburn et al., 2017and Ebert et al., 2017; Nawasreh et al. 2017). Four studies reported vertical jump test (Ageberg et al., 2008; Petschnig et al., 1998; Tengman et al., 2014; Beischer et al. 2017). Five studies have reported a side hop for endurance (Ageberg et al., 2008; Keays et al., 2003; Tengman et al., 2014; Gokeler et al., 2017; Beischer et al. 2017). A study reported Shuttle run and carioca for time (Keays et al. 2003). Stair hop test evaluated in one study (Qiestad et al. 2010).

More than 70% of studies used the single leg hop tests as a measurement of function within the battery of different tests completed. Only nine studies used multiple hop tests (34%), and sixteen papers (60%) reported limb symmetry index (LSI) comparing the injured with the uninjured leg. Three studies described the quality of movement while carrying out the test (e.g., dynamic knee valgus or knee flexion angle (Xergia et al., 2013; Ithurburn et al., 2017; Gokeler et al. 2017). Studies by Xergia et al., (2013) and Gokeler et al., (2017) assessed the quality of landing during SLHD following ACLR at 6 and 12 months postoperatively. Also, Ithurburn et al., (2017) examined the quality of landing during SLHD following ACLR at 7 and 24 months postoperatively. However, neither of three studies by Xergia et al., (2013); Ithurburn et al., (2017) and Gokeler et al., (2017) examined relative and absolute reliability following ACLR group at three and six months for 2D FPPA during SLHD.

Star Excursion Balance Test (SEBT)

Studies by Clagg et al. (2015) and Rohman et al. (2015) stated that at six months at the time of return to sport, participants' post-ACLR demonstrated reduced modified SEBT anterior reach in both involved and uninvolved limbs compared to uninjured participants, with no other group differences. Rohman et al. (2015) examined the LSI of the SEBT following ACLR from 4 to 7 months between the injured and non-injured limb. Further, the finding by Rohman et al. (2015) was that the LSI for the injured limb improved compared to the non-injured leg from 4 to 7 months following the ACLR. Clagg et al. (2015) found the poor score in the anterior reach of the YBT following ACLR at six months postoperatively on both limbs. However, neither of Clagg et al. (2015) and Rohman et al. (2015) established relative and absolute reliability during YBT following ACLR at three and six months.

Discussion

The first aim of the study was, to discover which study/studies utilised multiple measurement outcome tools (KOOS, TSK, YBT, 2D FPPA during SLS, and SLHD, and isokinetic knee strength) for ACLD knee and following ACLR at three and six months for the last 27 years. It was hypothesised that the poor outcome would demonstrate because the literature would not utilise multiple tools, especially at ACLD knee and following ACLR at three months to capture a comprehensive date before progressing to the next phase of rehabilitation and RTS. The findings of the review were that no study used a large combination of different tools to assess fear (TSK), KOOS (pain, symptoms, quality of life, Sport), neuromuscular control during (SLS, SLHD and YBT) and strength. The second aim was to discover relative and absolute reliability performed on ACLR patients at three and six months for the last 27 years. It hypothesised it would not identify relative and absolute reliability within the chosen primary outcomes following ACLR at three and six months. The findings of this reviewed showed no study examined relative and absolute reliability for ACLR at three and six months for a variety of tests.

The most significant finding of the present study was that all included papers used limited quantitative measurements to determine functional performance, except three studies done by Xergia et al., (2013); Ithurburn et al., (2017) and Gokeler et al., (2017) where they also described the quality of movement while carrying the test. In the last twenty-seven years, most of the studies included in this review focused on the distance covered during hop tests especially the single leg hop test (70% of the studies) and studies by Clagg et al., (2015) and Rohman et al., (2015) examined the modified SEBT following ACLR. Regarding the patient-reported outcomes, the focus was on the KOOS and TSK questionnaires. Considering isokinetic knee strength tests, three studies by Heijne et al., (2009); Liu-Ambrose et al., (2003) and Tengman et al., (2014) performed concentric and eccentric contraction of knee flexors and knee extensors who undergone ACLR.

Patient Reported Outcomes

Most of the studies included in this review were focusing on KOOS, IKDC and TSK. The Tegner activity scale is one of the most commonly used activity scales in ACL rehabilitation (Lysholm & Tegner 2007), while estimates of a more general physical activity level are less common in studies after the ACL injury. Briggs et al., (2009) examined reliability and validity of TSK (r= 0.80, MDC= 1) on a patient with an ACL injury and following ACLR at 6,9, 12, and 24 months. However, to reliably capture the general activity level in any population is a challenge (Poppel et al. 2010).

Seven studies have described the KOOS score (Ageberg et al., 2008; Frobell et al., 2010; Heijne et al., 2009; Tengman et al., 2014; Beischer et al., 2017; Toole et al., 2017; Ithurburn et al. 2017), and Tengman et al., (2014) reported Tampa scale for kinesophobia (TSK) in the included review studies. Considering TSK and correlation with KOOS knee function, there was the negative correlation (r= -0.50, r= -0.043 P<0.05) between the TSK and knee-related quality of life and pain (KOOS), no association found between KOOS and age, and symptoms (KOOS) (Kvist et al., 2005). Tengman et al., (2014) found a negative association for fear of re-injury and knee function for KOOS symptom (P = 0.004, r = − 0.297) after 20 years follow up on 113 patients (refer to table 2). However, there was no published study that examined the correlation between TSK and the function of the knee in sports population (KOOS). Therefore, further investigation of this relationship is needed before it can be recommended for use in preoperative ACL subjects and ACLR subjects at 3 and 6 months.

Studies by Kvist et al., (2005); Tripp et al., (2011) and Tengman et al. (2014) used TSK on patients who underwent ACLR. Kvist et al., (2005) reported 53% of the patients who undergone ACLR had returned to pre-injury activity level, and 24% did not RTS following ACLR at 3-4 years because of their fear of re-injury. The same issues have also reported on two studies (Bjordal et al., 1997 and Mikkelsen et al. 2000) as a primary reason for not return to pre-injury activity levels.

Bjordal et al., (1997) reported the fear of re-injury rate of 22.9% for male soccer players older than 39 years old and 33% for women under the age of 19 years following ACL injury from 1982 to 1991. However, Bjordal et al., (1997) reported the information of participants with different activity level. Bjordal et al. (1997) utilised a mixed number of unequal males and females, which may skew the subsequent data analysis scores. This is important because finding from male professional soccer players information in the study by Bjordal et al. (1997) cannot be applied to amateur women players. However, there is no published research has reported utilizing both KOOS and TSK questionnaire on ACL injury (preoperative) on an adult male population following ACLR at 3 and 6 months. Therefore, further investigation of the relative and absolute reliability of the TSK and KOOS required before it can be recommended for utilization in preoperative ACL subjects and ACLR subjects at 3 and 6 months.

Strength measurement

This review shows that three out of twenty-one studies have reported knee strength measurement with a mode of concentric and eccentric contractions of knee flexors and extensor who undergone ACLR surgeries with autograft of BPTB and hamstring (Heijne et al., 2009; Liu-Ambrose et al., 2003; Tengman et al. 2014). Furthermore, thirteen of twenty-one studies reported knee strength measurement with a mode of concentric contractions of knee flexors and extensors and six of twenty-one studies reported knee strength measurement with the mode of isometric contractions following ACLR.

Liu-Ambrose et al., (2003) recruited ten patients with age of 18-36 years old who had undergone unilateral ACLR and randomly assigned to one of following 12 weeks of strength training (ST), proprioceptive training (PT) and establish the determinant of functional ability for operated limb after six months surgery. The outcome measure of isokinetic knee strength test was peak torque of hamstring muscles and average concentric and eccentric torques of quadriceps and hamstring muscles (Liu-Ambrose et al., 2003). However, Liu-Ambrose et al. (2003) did not normalize peak torque of hamstring and average peak torques of quadriceps and hamstring muscles to measure limb symmetry index (LSI).

Average torque value is significantly different during acceleration and deceleration portions of the torque curve from 0 to 90 degrees of knee flexion and extension (Harding et al. 1990). In contrast, peak torque value did not differ significantly (Harding et al. 1990). Harding et al., (1990) tested knee flexion and extension through 90 degrees, the peak torque and average torque did not differ significantly through the range from 10 to 80 degrees. Ten to 90 degrees is the range of true isokinetic movement (constant angular velocity) which correctly excluded overshooting torque during first 10 degrees knee flexion and extension. Furthermore, Liu-Ambrose et al. (2003) failed to report the relative and absolute reliability of their primary outcome measures.

Heijne et al., (2009) recruited 64 patients (M=35 F=29) to investigate preoperative factors that may predict good outcomes as measured with concentric and eccentric muscle torques of the knee extensors and knee flexors at 90/s within 10–90 of knee flexion. However, Heijne et al. (2009) failed to report this outcome measure in terms of normalised peak torque in both preoperative and twelve months after ACLR periods so making comparison difficult.

Tengman et al. (2014) recruited 103 participants into three groups (refer to table 2) to measure peak torque in concentric and eccentric knee flexors and knee extensors more than 20 years follow-up.

The ACLR group, shown 13%-14% deficit for knee extension peak torque compared to non-injured knee with no significant side-to-side differences in knee flexion peak torque (Tengman et al., 2014). The ACL injured group with physiotherapy treatment had a smaller (7%) side-to-side difference for concentric knee extension peak torque, while also a side-to-side difference for eccentric contractions of 12%, almost twice the size of the concentric side difference. Deficits were also found in eccentric knee flexion with a 10% torque reduction in the injured leg, whereas no side differences found in the concentric phase (Tengman et al., 2014). In both groups, the eccentric knee extension peak torque reduced, but interestingly, the eccentric knee flexion peak torque was impaired only for the ACL injured group with physiotherapy. The deficit in the eccentric knee flexion peak torque was due to 38% higher tibial translation in the ACL-injured knee compared with the non-injured knee during isokinetic testing, while there were no differences in translation for concentric contractions (Kvist et al., 2001).

There is only one published study (Tengman 2014) that reported relative reliability on ACL injured patients and ACLR patients when measuring eccentric and concentric contractions of knee flexors and extensors yet. However, there is no published study that utilised isokinetic knee strength test with mode of concentric and eccentric contractions for ACLD subjects and compared with the control group. Also, the examination of the relative and absolute reliability of isokinetic knee extension and flexion is needed before it can be recommended for use following ACLR subjects at 3 and 6 months.

Single leg hop test

Single leg hop for distance assessed in nineteen studies (70%) of those included in the review to determine the functional performance of patients following ACL reconstruction and ACLD subjects. None of the included studies utilised SLHD at ACLD knee alongside 2D FPPA to determine the distance (cm) and quality of landing (knee valgus) between an injured leg and non-injured limb. Single leg landing task such as SLHD is prevalent in the clinical environment because it is easy and quick to perform and reliable and valid measures of the lower- limb functional joint stability (Clark 2001; Clark et al., 2002 and Kivlan and Martin 2012). One of nineteen studies (Reid, Birmingham, Stratford, Alcock, and Giffin 2007) provided relative and absolute reliability in patients following ACLR at four months postoperatively.

Three of nineteen studies (Xergia et al., 2013; Ithurburn et al., 2017 and Gokeler et al. 2017) reported on the quality of single leg hop distance during landing to measure kinematic differences, propulsion and landing phase parameters on patients following ACLR at 6 and 12 months (Xergia et al., 2013 and Gokeler et al. 2017) and 7and 24 months (Ithurburn et al. 2017). Gokeler et al. (2017) reported that 67.9% of patients (m=22, f=6) passed the LESS<5 criteria during bilateral landing tasks by utilising two standard 60-Hz video camera capturing frontal plane and sagittal plane views of the jump landing (Gokeler et al. 2010). The observing and quantifying of sagittal plane single leg landing asymmetries following ACLR could be performed in clinical settings, either using 3D or using 2D video techniques. Studies by Ekegren et al., (2009); McLean et al., (2005); Mizner et al., (2012) and Munro et al. (2012) reported that the use of 2D video is a valid and reliable measure of knee kinematics.

Ithurburn et al. (2017) utilised 3D motion analysis to capture knee flexion angle excursion, peak internal knee extension moment (Nm/kg) and peak trunk flexion during four single-hop tests. However, Ithurburn et al. (2017) failed to report a result at two years following ACLR in 48 young athletes. Laughlin et al. (2011) stated reduced knee flexion angle, which they found might be a compensatory strategy in subjects following ACLR who have persistent knee extensor weakness. Furthermore, limited flexion of ankle, knee and hip joints during landing also results in a stiff landing pattern, which may increase ACL loading and so the risk of re-injury (Laughlin et al. 2011)

When considering acceptable LSI values for hop test performance to return safely to more intense sports specific activity following ACLR these have been reported as 90% (Myer et al., 2011; Thomee et al. 2011). Few studies presented evidence of patient achieving this. Xergia et al. (2013) reported 5% of patients had greater than 90% LSI in single, triple and crossover hop distances following ACLR at 6-9 months postoperatively. Gokeler et al. (2017) reported 78.5% of (28 patients, m=22, f=6) patients passed LSI>90% for SLHD, 85% for triple leg hop and 50% for the side hop following ACLR at six months. However, in the cohort study by Hannon et al. (2017) reported a decrease of 25.5% of quadriceps muscle strength of the uninvolved limb on 31 ACL injured athletes after twenty –three days after the ACL injury. Therefore, by having bilateral quadriceps deficit after 23 days of ACL injury, utilising un-injured limb, as a reference limb would appear to require more cautious when we are utilising LSI passed criteria.

The utilisation of non-injured limb as reference limb after rupture of ACL is a significant weakness of the above-included studies in using the LSI measurement only without comparing to norm values. Neglecting the examination of the ACLD injured and non-injured limb comparing to control group and compare the ACLR group at 3 and 6 months with the control group, which then may cause a bilateral deficit rather than normalisation of deficiencies in the injured leg. Therefore, further investigation of the relative and absolute reliability and 2D FPPA of single leg hop for distance is needed before it can be recommended for use following ACLR subjects at three and six months.

Single leg squat (SLS)

One of the twenty-six studies (Rohman et al., 2015) reported SLS ability, in 38 patients (mean age=26 years old) following ACLR at both four, and six months postoperatively. Single leg squat improved at the involved limb from 4 to 6 months (80.1°to 86.5°) and uninvolved limb from (87.1° to 97.0°), (knee flexion angle) indicating that the non-injured leg shown more significant improvement than injured limb (Rohman et al. 2015). However, Hall et al. (2015) reported 33 patients (mean age=15-50 years old) who underwent ACLR at six months postoperatively, showing 45% (15 of 33 patients) of the patients demonstrated poor performance on SLS of the operative limb. Those with good performance had a mean age of 24.2 years (ranges, 17-48 years) compared with 33.3 years (range from=15-42 years) for those with poor performance (Hall et al. 2015).

Furthermore, Hall et al. (2015) stated that those patients with poor performance demonstrated decreased hip abduction strength on the operated limb, decreased SLHD, and lower IKDC. However, Hall et al., (2015) and Rohman et al. (2015) did not utilise the quality assessment of SLS movement pattern to detect ACL injury risk factors, progress during rehabilitation and readiness for return to sport. Willson and Davis (2008) recruited 20 females with Patellofemoral pain syndrome (PFPS) and 20 healthy matched female controls to measure knee and hip joint rotation during SLS and running tasks with 2D FPPA and 3D motion analysis. Willson and Davis (2008) reported FPPA values representing the medial displacement of the knee during SLS associated with increased hip adduction (r=0.32-0.38) and knee external rotation (r=0.48 -0.55) on twenty females with PFPS. Also compared with the control group, patients with PFPS demonstrated more significant medial displacement of the knee joint during SLS task.

There is no published study to examine the quality of landing during SLS and SLHD for ACLD subjects and following ACLR at three and six months with 2D FPPA. Furthermore, there is no study establish relative and absolute reliability for 2D FPPA during SLS, and SLHD following ACLR at three and six months. Therefore, further investigation of the relative and absolute reliability of 2D FPPA and QASLS are needed before it can be recommended for use for ACLR subjects at 3 and 6 months. If the reliability and measurement error of these screening methods can be established, clinicians will be able to use the tests with confidence while also being able to evaluate individual performance more informatively.

Postural control

Clagg et al., (2015) and Rohman et al. 2015) utilised SEBT following ACLR but used different measurement methods. Rohman et a. (2015) recruited 38 patients (mean age=26 years) following ACLR to measure LSI of anterior-lateral and anterior-medial reach distance at 4, and 6 months postoperatively. The LSI changed significantly for anterior-medial reach (from 96.1% to 99.0%) and anterior-lateral reach (from 96.7% to 98.4%) from 4 to 6 months. Furthermore, Rohman et al. (2015) also reported that the involved limb reach distance (from 64.8 cm to 72.1 cm) shown greater improvement to un-involved limb reach distance (from 67.1cm to 72.9cm) from 4 to 6 months. The most important finding was that the un-involved limb ability did not improve, as this could undermine the utility of LSI testing time before surgery. LSI scoring appears to be an appropriate method of detecting functional improvement and evaluating rehabilitation progress. However, Rohman et al. (2015) did not report norms value of patients who underwent ACLR before surgery, which may lead to misleading high LSI, which then may reflect a bilateral strength deficit rather than normalisation of deficits in the injured limb.

Clagg et al. (2015) reported that the ACLR group showed worse anterior reach performance on both the involved and uninvolved limbs compared to the control group with no difference between two groups in both posterior-medial and posterior-lateral reach directions at the time of return to play (6.7 months post ACLR). When considering SEBT as a predictor of lower extremity injuries, Plisky et al. (2006) reported that anterior reach differences between left and right higher than 4cm were 2.5 times associated with sustaining a lower extremity injury in high school basketball players. The variation in the anterior reach between the ACLR and control groups was 5.1 cm and 4.1 cm for the involved versus non-preferred and uninvolved versus preferred limbs, respectively (Clagg et al. 2015). However, there is no published study has reported YBT on ACLD comparing injured limb to non-injured limb. Further, there is no study established relative and absolute reliability for YBT following ACLR at three and six months and compared to the control group. Therefore, it requires further investigation before it can be recommended to the clinician to use the criteria with confidence for ACLD group and ACLR participants.

The findings by Delahunt et al. (2013) was not in agreement with Clagg et al. (2015). The latter reported that ACLR patients' reach distances on the posterior medial and posterior-lateral directions of the SEBT decreased. Still, no difference in the performance of the anterior reach, in females an average of 2.9 years (range= 10 months to 6 years) after ACLR compared to controls. The findings of Delahunt et al. (2013) agreed with Herrington et al. (2009). The latter reported similar deficits in reach differences in twenty-five ACL-deficient patients with a mean time of 11 months since the original injury. These differences might be related to sample characteristics, performing the SEBT at different times, mixed results of male and female data, the difference activity level of samples, and difference graft types that may relate to the different statistical findings.

There are potential limitations includes utilising the isokinetic dynamometer in the standard clinical context since the isokinetic dynamometer is expensive and not easily accessible to practitioners. Further, there is weak to moderate and often insignificant relationships exist between the isokinetic muscle strength and many FPTs. Therefore, in the absence of isokinetic dynamometer, further research should consider utilising resistance machines. Further, resistance machine such as leg press, leg extension, and leg curl are widely available to the athletes and practitioners in the local communities. Potential limitations also include measurement reliability is population-specific and, therefore, may only be generalised to the adult male population from the United Arab of Emirates region in the present study. Consequently, the results of this thesis may be only generalised to a community with the ACLR group at three and six months postoperatively. Therefore, once the relative and absolute reliability for the ACLR group at three and six months has been established, future research should then assess its criteria related validity.

Conclusion

The findings of the systematic review showed that there are no studies utilising multiple tools (KOOS, TSK, YBT, 2D FPPA during SLS and SLHD and isokinetic knee strength test with the mode of concentric and eccentric contractions in assessing outcome in the last 27 years for ACLD or ACLR.

The SLHD and isokinetic knee strength tests were the most common tools utilised among studies as a criterion to RTS. Three studies by Xergia et al., (2013); Ithurburn et al., (2017) and Gokeler et al., (2017) examined the quality of landing during SLHD. For isokinetic knee strength tests, three studies by Heijne et al. (2009); Liu-Ambrose et al., (2003) and Tengman et al., (2014) performed concentric and eccentric contraction of knee flexors and knee extensors who underwent ACLR for the last twenty-seven years. Clagg et al. (2015) and Rohman et al. (2015) utilised SEBT following ACLR at 4 and 6 months postoperatively. However, none of the above studies used multiple tools for ACLD subjects and following ACLR at three and six months. Assessing the fear of re-injury, quality of life, pain, symptoms, static and dynamic neuromuscular control, strength, force production, force absorption, proper knee alignment during the single leg tasks is necessary for monitoring the patients following ACLR before progress the patients to the next phase of rehabilitation.

For a practitioner to confidently perform all above tests, the relative and absolute reliability must be known in an ACL specific population. Lack of reliability and measurement precision undermine the validity of raw data and compromise data analysis procedures and practitioners' decision-making (Batterham & George, 2003; Clark et al., 2016). No study examined relative and absolute reliability of KOOS, TSK, YBT, 2D FPPA during SLS and SLHD, and isokinetic knee strength test following ACLR at three and six months and compared to the control group. Therefore, it requires further investigation before it can be recommended to the clinician to use the criteria with confidence in ACL injury and ACLR participants.

Chapter 3

Subjective and objective measurement from anterior cruciate ligament deficient male patients from United Arab of Emirates

Summary

The aim of this chapter was to compare the results of a battery of tests: KOOS, TSK, YBT, isokinetic knee strength test and 2D FPPA during SLS and SLHD between ACLD patients who were candidate's for ACLR surgery and an uninjured control group. The findings of the current study demonstrated that the control group performed better in all tests except for isokinetic knee strength (normalised peak torque for hamstring and quadriceps) and QASLS during SLHD tests compared to both limbs in ACLD group. They were symmetrical in the YBT, SLHD, 2D FPPA for SLS and SLHD, QASLS for SLS and SLHD tasks, normalised peak torque concentric hamstring and KOOS (symptoms and ADL) tests when comparing the injured to non-injured limb. Other findings demonstrated that there were significant side to side differences in the normalised peak torque for eccentric hamstring and concentric and eccentric contractions for the quadriceps muscle, KOOS (QOL, pain and sport) and TSK tests when compared between the ACLD and control limbs. Other findings demonstrated that the ACLD group also showed bilateral quadriceps deficit after an ACL injury, compared to typical norms from the literature. Therefore, pre-operative rehabilitation is recommended to restore full knee range of motion, strengthening bilateral deficit quadriceps muscle after an ACL injury, but patients must be carefully assessed and monitored as despite undertaking a pre-operative rehabilitation programme, this ACLD group failed to achieve symmetry in all tests. Also using the LSI may underestimate performance deficit.

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Introduction

Most athletes who undergo anterior cruciate ligament reconstruction (ACLR) plan to return to their pre-injury level of the sport (Feucht et al. 2016). Considering the mechanism of ACL injuries, 70% to 84% of the ACL injury occurs without contact (Boden et al., 2009; Fauno and Wulf 2006; McNair 1990). The ACL injuries result from cutting or stopping manoeuvre combined with deceleration and landing from a jump (Fauno, Wulf 2006; Boden et al. 2000). The alignment is associated with non-contact ACL injuries occur during a deceleration task with bodyweight shifted over the injured leg and the plantar surface of the foot fixed flat on the ground (Boden et al. 2000). Knee alignment associated with non-contact ACL injury involves lower flexion, valgus and internal rotation (Koga et al. 2010).

The secondary ACL injuries occur in the same limb and an opposite limb compared to individuals without previous ACL injury (Bryant et al., 2008; Paterno et al., 2010; Wiggins et al. 2016). Wiggins et al. (2016) reported the incidence of recurrent ACL injury after ACLR is approximately 15%; with the same limb injury rate of 7% and an opposite limb injury rate of 8%. The high rate of secondary ACL injury in young athletes who return to sport after ACLR equates to a 30 to 40 times greater risk of an ACL injury compared with non-injured athletes (Wiggins et al. 2016). An ACL injury and ACLR are associated with increased risk of tibiofemoral and patellofemoral osteoarthritis with prevalence ranging from 0% to 13% in isolated ACLD knees and 21% to 48% for patient with combined injuries (Qiestad et al. 2010). Proprioceptive deficits after ACL injury may be a factor related to both giving away and higher incidence of subsequent injury, which in turn may contribute to knee osteoarthritis (Roberts et al. 1999).

A scoping review by Burgi et al., (2019) reported only 26% of the RTS decisions were based on functional testing (hop testing), patient report and performance-based criteria. The majority of decisions to allow RTS were clinically based assessment focusing on swelling, pain, range of motion and joint laxity (Burgi et al. 2019).

Furthermore, Burgi et al. (2019) reported the 85% of RTS decisions were based on time (before nine months) and 42% of RTP based on movement impairment. Even though most of the athletes achieve an acceptable level of function, the RTS rates after ACLR are still low (Thomee et al. 2011).

Despite the fact, the isokinetic knee strength evaluation after ACLR commonly used to evaluate RTS readiness; these measures have not validated as a useful predictor of successful RTS (Undheim et al. 2015). Historically, measurements were taken on both the involved and non-involved limb, and LSI are recorded, with goals for the injured leg to be within 10% (Munro and Herrington 2011 and Thomee et al. 2011). However, Wellsandt et al. (2017) reported the comparing the involved side to the non-involved side at the time of release was not an appropriate comparison because the non-involved limb after ACL injury will be neglected and possible neuromuscular changes. Therefore, the higher rate of contralateral ACL tears has raised concerns regarding this approach (Wellsandt et al. 2017). Quadriceps muscle strength has examined extensively, and findings consistently demonstrate quadriceps strength asymmetries of up to 80% at the time of RTS and up to 2 years after ACLR surgery (Chung et al., 2015; Lepley et al., 2015; Palmieri-Smith et al., 2008 and Pietrosimone et al. 2016). However, based on the systematic review in chapter 2, there is no consistency to the use of outcome measures, and studies have failed to use a comprehensive range of outcome measures (quantitative and qualitative assessments) to explore the patient outcome and functional performance levels fully.

Studies by Koga et al., (2010) and Krosshaug et al., (2007) stated that the majority of ACL injuries occur during unilateral movements in the frontal and transverse planes of motion other than the sagittal plane. Further, having an understanding of landing kinematics in the sagittal plane alone, may not provide sufficient insight to understand the underpinning mechanisms involved in the faulty movement mechanism after ACL injury on both injured and non-injured limb compared to the control group in this study. A battery of hop tests is potentially restricting the identification of relevant functional performance deficit in other planes. During high-level sports (contact, pivoting, and competitive) an athlete has to move as quickly as possible in all three planes of movement, multiple directions of tests might better employ more challenging functional performance movements and increase the sensitivity for detecting deficit. Itoh, Kuroska, Yoshiya, Ichihashi, and Mizuno (1998) found 68%, 58%, 44%, and 42% abnormal symmetry during the figure of eight hops, up down hop, side hop and single leg hop in 50 patients with unilateral ACLD. Gustavsson, Netter, and Thomee (2006) reported high ICC values ranged from 0.85 to 0.97 for the three maximum hop tests and two endurance hop test (side hop and square hop) in healthy (M=9, F=6), ACLD (M=18, F=12) and following ACLR (M=25, F=10). During the two endurance hop tests, the patients performed as many hops as possible in 30 seconds periods with the distance of 40 cm, to develop muscle fatigue and to demand knee stability in the frontal plane of motion (Gustavsson, Netter and Thomee, 2006).

In the current study, adult male patients who decided to elect for ACLR participated in the study. An adult male population was used in the present study because recruiting female subjects in the Arab countries are very difficult due to the cultural boundaries. The ACLD and the ACLR subjects in the present study undertook rehabilitation at Alahli sports medicine department in UAE. Pre-operative rehabilitation was performed for the ACLD subjects to reduce swelling, restoring knee extension range of motion, gait re-education and quadriceps strength symmetry (Adams et al., 2012). Pre-operative quadriceps muscle symmetry is a meaningful predictor of an individual's ability to pass or fail return to sport criteria six months after surgery (Hartigan et al., 2012). Adams et al. (2012) stated that criteria rather than timeline-based rehabilitation accepted as the gold standard. However, at Alahli sports medicine department, the return to play criteria following ACLR is still timeline-based rehabilitation. Therefore, this is the first study using multiple tests to examine the ACLD and the ACLR subjects based on criteria rather than time. The criteria measures used in the current study included knee osteoarthritis outcome score (KOOS), Tampa scale of kinesiophobia (TSK), 2- dimensional frontal plane projection angle (FPPA) during a single leg squat (SLS) and single-leg hop for distance (SLHD), Y anterior reach balance test and isokinetic knee strength test.

In the Middle East region, the incidence of ACL injuries is high among recreational and professional athletes, and the majority of these patients prefer to have ACLR surgery (Rekik et al., 2018). Rekik et al. (2018) reported the overall ACL injury rate in professional male soccer players competing in the Middle East was 0.076 injuries/1000 hours of exposure. Of 37 ACL ruptured injuries reported in their study, 22 occurred during matches and 15 during training with an injury incidence of 0.41 (95% CI 0.26 to 0.63) and 0.4 (95% CI 0.02 to 0.06) per 1000 hours exposure, respectively. Therefore, injury incidence during the competition was significantly higher than training, with the average ACL related time-loss time to surgery plus rehabilitation being 225 days (7.5 months) (Rekik et al., 2018).

Rekik et al. (2018) demonstrated that each team involved in the Qatar soccer league might have approximately one ACL injury every two seasons. The ACL injuries occurring during Qatar soccer league matches were similar to the UEFA study (0.41 versus 0.34 injuries/1000 hours), respectively) (Walden et al., 2016). However, Rekik et al. (2018) demonstrated that, unlike the UEFA study by Walden et al. (2016), the ACL injuries occurring during training were higher. In Qatar, during the five seasons studied by Rekik et al. (2018), 12 teams played 22 local league matches per season. In the Europe league (England, Spain and Italy etc), there are 20 teams playing a minimum of 38 domestic games per season, more if qualifying for the UEFA champions league. Overall, Qatar's number of games over one season is considerably lower compared with most European leagues. Therefore, the ratio of training to match exposure is higher in Qatar and may account for the greater ACL injury rate in practice (Rekik et al., 2018). There has been no data reported on overall outcome or specific outcome measures following an ACL injury and ACLR in the United Arab Emirates.

Assessing fear of re-injury, symptoms, quality of life, isokinetic knee strength test, and neuromuscular control during single leg landing tasks with 2D FPPA after ACL injuries are significant for clinicians. A comparison between baseline data (ACLD knee) and following ACLR at three and six months is imperative because improving knee function in the pre-operative stage positively affects post-surgical outcome (Eitzen et al., 2009; Adams et al. 2012; Eitzen et al., 2010). Pre-operative quadriceps strength symmetry has shown to be a meaningful predictor of an individual's ability to return to jogging at three months and return to sport at six months following ACLR (Hartigan et al. 2012). Also, quadriceps strength pre-operatively predicts IKDC scores and influences self-reported knee function following ACLR at six months (Logerstedt et al., 2013). A quadriceps strength deficit at the pre-operative phase is also predictive of an ongoing strength deficiency following ACLR at two years (Eitzen et al., 2009). Therefore, having baseline data for the ACLD knee in the current study might help identify those patients with optimal outcomes following ACLR at three and six months post-operatively, and also deficits which relate to poor performance during these periods. In the current study, a control group is also used for comparison, because though often after the ACL injuries, the non-injured limb would be used as a reference limb for side-to-side comparison there is a risk that this limb has detrained and atrophied so does not reflect normal performance levels of the patient's limb. Hannon et al. (2017) found a 25.5% quadriceps deficit after 23 days of ACL injury in non-involved knee compared to the control group.

This study assessed the outcome measurement between injured to non-injured limb for ACL injury subjects compared to the control group (chapter 3) and following ACLR at three and six months postoperatively (chapter 4) with the same ACLD and ACLR subjects to discover fear, knee strength and quality of landing. Therefore, this study aimed to examine the results of a KOOS, TSK, YBT, isokinetic knee strength test and 2D FPPA during SLS and SLHD between ACLD patients who were candidates for ACLR surgery and a control group. Further, to compare an ACL injured limb to non-injured limb, an ACL injured limb to control limb and non-injured limb to control leg. It was hypothesised that the control limb will perform better results than the ACLD group in both injured and non-injured limb.

Method

Participants

A total of 44 participants who met inclusion criteria were enrolled in this study: seventeen recreationally active participants, all male subjects with ACL injuries and 27 healthy controls. Table 1 displays the characteristics of the participants for both groups. All of the participants who were part of Alahli sports club squad, or patients of the Up and Running sports medicine clinic in the United Arab of Emirates, volunteered for the study. All the above participants referred by orthopaedic surgeons and sports physician for this study. All participants were tested at Rashid stadium at the Alahli sports medicine department, asking them to wear comfortable clothes and training shoes. Before the functional test assessments, all participants had full knee range of motion and no knee effusion. Leg length was measured from the anterior superior iliac spine to the distal tip of the medial malleolus using a standard tape measure while participants lay supine (Gribble & Hertel, 2003) and used to normalise reach and hop distances. Limb dominance was determined by asking participants which limb they would predominantly use to kick a ball. Limb dominance was required for calculation of LSI scores. The same examiner evaluated all subjects. The primary outcomes consisted of the following measures conducted in sequence: 1. KOOS, 2. TSK, 3. YANT 4. SLS task with 2D FPPA and QASLS score sheet, 5. Single leg hop for distance with 2D FPPA and QASLS score sheet, and 6. Isokinetic knee strength test (Biodex). Before the functional testing assessment, all subjects had completed a 10 minutes warm up on a stationary bike followed by stretching. Entry inclusion criteria for this study are outlined below. A subject who was diagnosed by an orthopaedic surgeon with an ACL rupture and candidate for ACL reconstruction.

Exclusion criteria were including a posterior cruciate ligament (PCL) rupture, medial collateral ligament (MCL) grade II and III, lateral collateral ligament (LCL) grade II, and III, alongside ACL injury.

The age of all participants was between 18 and 45 years of age. This age range was selected to represent the young, recreational population to whom the results of the study are most likely to be applied.

All participants were required to participate in a minimum of 30 minutes of physical activity three times a week regularly over the past six months, which included recreational and competitive sports.
The project approved by the University Research and Ethics Committee (HSR1617-63) and all participants gave written informed consent before participation. Mean time from injury to surgery was 32 days. All the participants had to have regained their full knee ROM (knee flexion and knee extension) and have no swelling before testing.

Table 1: Descriptive data of included both group of subjects (Mean± Standard deviation)

	ACL-Injured group (n=17)	Control group (n=27)
Age (years)	24.4±6.9	25.67±4.95
Height (cm)	177±9.5	168.5±8.95
Mass (kg)	77.5±13.9	59.2±8.70
Sex(male/female)	17/0	27/0
Leg length (%)	93.2±4.9	87.81±5.31
Sports (number)		
Basketball	4	8
Handball	2	5
Volleyball	4	7
Football	7	7
Limb dominance (right/left)	13/4	22/5
Injured limb (right/left)	14/3	N/A
Mean time from injury to surgery(days)	±32	

Patient Reported outcome measure

All participants asked to fill up two below subjective questionnaires.

Tampa Scale of Kinesiophobia (TSK)

The TSK is a 17-item measure that assesses fear of movement, each item on a four-point Likert scale with scoring alternatives ranging from "strongly disagree" to "strongly agree". Items 4, 8,12 and 16 are inversely scored (Table 2). The removal of four inversely score from TSK questionnaire was advocated the short version TSK-11 because this will increase the internal consistency of the measure and reduce administration time (Clark, 1998; Goubert et al., 200); Roelofs et al., 2004). Total scores range from 17 to 68, with higher scores reflecting greater fear of movement (Woby, Roach, Urmston and Watson 2005). High reliability of the TSK and short version of TSK-11 (TSK: ICC=0.82, SEM 3.16; good internal consistency (TSK: a=0.76) and cutoff scores of four have reported by Woby, Roach, Urmston and Watson (2005) on patients with chronic LBP. Concerning cutoff scores, a reduction of at least four points on the TSK will maximize the likelihood of correctly identifying an essential decrease in fear of movement (Woby, Roach, Urmston and Watson 2005).

Table 2: Sample of TSK questionnaire

1. I'm afraid that I might injury myself in I exercise	Strongly disagree	Disagree	Agree	Strongly agree
2. If I were to try to overcome it, my pain would increase	Strongly disagree	Disagree	Agree	Strongly agree
3. My body is telling me I have something dangerously wrong	Strongly disagree	Disagree	Agree	Strongly agree
4. My pain would probably be relieved if I were to exercise	Strongly disagree	Disagree	Agree	Strongly agree
5. People aren't taking my medical condition seriously enough	Strongly disagree	Disagree	Agree	Strongly agree
6. My accident has put my body at risk for the rest of my life	Strongly disagree	Disagree	Agree	Strongly agree
7. Pain always means I have injured my body	Strongly disagree	Disagree	Agree	Strongly agree
8. Just because something aggravates my pain does not mean it is dangerous	Strongly disagree	Disagree	Agree	Strongly agree
9. I am afraid that I might injure myself accidentally	Strongly disagree	Disagree	Agree	Strongly agree
10. Simply being careful that I do not make any unnecessary movements is the safest thing I can do to prevent my pain from worsening	Strongly disagree	Disagree	Agree	Strongly agree
11. I wouldn't have this much pain if there weren't something potentially dangerous going on in my body	Strongly disagree	Disagree	Agree	Strongly agree
12. Although my condition is painful, I would be better off if I were physically active	Strongly disagree	Disagree	Agree	Strongly agree
13. Pain lets me know when to stop exercising so that I don't injure myself	Strongly disagree	Disagree	Agree	Strongly agree
14. It's really not safe for a person with a condition like mine to be physically active	Strongly disagree	Disagree	Agree	Strongly agree
15. I can't do all the things normal people do because it's too easy for me to get injured	Strongly disagree	Disagree	Agree	Strongly agree
16. Even though something is causing me a lot of pain, I don't think it's actually dangerous	Strongly disagree	Disagree	Agree	Strongly agree
17. No one should have to exercise when he/she is in pain	Strongly disagree	Disagree	Agree	Strongly agree

Knee Osteoarthritis Outcome Score (KOOS)

The Knee Osteoarthritis Outcome Score (KOOS) is a 42 item self-administrated questionnaire constructed for patients with osteoarthritis and ACL rupture (Roos, Roos, Lohmander, Ekdahl, Beynnon 1998). It consists of five sub-scales including pain, symptoms, function in daily living, function in sports and recreation and knee-related quality of life. A score calculated within every sub-scale, where 100 indicate no problem and 0 indicates a severe problem (refer to the link for the five subscales of the KOOS questionnaire www.koos.nu). Salavati et al. (2011) established high reliability (ICC, SEMs) of the KOOS subscales; pain (ICC =0.93; SEM= 2.2), Symptoms (ICC=0.85; SEM=3.1), activities of daily living (ICC=0.91; SEM=2.1), function in sports and recreation (ICC=0.75; SEM=2.1), and knee-related quality of life (ICC=0.89; SEM=2.6). Considering the KOOS cutoff points, Barenius et al. (2013) reported following cutoffs: >90 for pain, >84 for symptoms >91 for ADL>80 for sports/Recreation, and >81for QOL.

Qualitative assessment of Single Leg Squat (SLS)

Participants asked to take a single leg stance on the front of a digital video camera (Sony Handycam DCR-HC37). The camera was sampling at 25Hz with a height of 60cm on a tripod, two meters away from the participants. Further, the tripod's height of the camera aligned to the knee joint, and perpendicular to the frontal plane of the subject. Digital video footage was recorded at a standard 10x optical zoom throughout each trial to standardise the camera position between participants. The data collected during SLS and SLHD for each participant transferred from a camera to a computer.

For 2D analysis, markers were placed on the lower extremity of each participant to approximate the radiographic landmarks employed by Willson et al. (2006). Markers placed at the midpoint of the ankle malleoli for the centre of the ankle joint, the centre of the femoral condyles to approximate the centre of the knee joint, and on the proximal thigh at the midpoint of the line from the anterior superior iliac spine to the knee marker (Figure 1). Markers used to determine joint centres as it has shown to increase intra- and inter-rater reliability in comparison to manual digitisation of joint centres via video (Bartlett et al. 2006). These markers used for FPPA of the knee to detect knee valgus from digital images using Quintic software package (9.03 version 29).

Figure 1: 2D marker placement for the measurement of Frontal Plane Projection Angle during SLS an SLHD.

An adjustable stool placed behind the subject at the height that represented the distance from the floor each subject would need to assume to achieve 45° knee flexion, over five seconds (Willson et al., 2006 and Munro et al. 2012).

Subjects asked to squat until a buttock of the subject lightly touched the stool with their seat. Knee flexion angle was checked during practice trials using a standard goniometer (Gaiam-Pro) then observed by the same examiner throughout the tests. There was also an electronic counter for each participant over these five seconds in which the first count initiates the movement; the third indicates the lowest point of the squat, and the fifth marks the end. Trials were only accepted if the participant squatted within the desired degrees of knee flexion and they maintained their balance throughout.

Participants were allowed to practice SLS trials until they felt comfortable. After familiarisation, each participant performed three trials of each test to obtain the mean value. Both legs were tested and analysed for SLS and SLHD tasks. Participants were allowed thirty seconds rest between practices and two minutes between tasks. The qualitative analysis of single leg squat (QASLS) is a new scoring system designed to identify segmental sub-optimal behaviour following the performance of a single leg squat. The scoring sheet is shown in table (3) and examples of appropriate and inappropriate movement strategies in a table (4).

A qualitative scoring system was devised by one of the authors (LH) based on the previously reported scoring systems of Crossley et al. (2011) and Whatman et al. (2013). It involved dichotomous scoring of the movement strategy occurring in individual body regions (arm, trunk, pelvis, thigh, knee, foot).

A qualitative scoring system was defined as a zero for appropriate method (of the relevant body part) and one point for each inappropriate movement which occurred, for each body part. Further, the best overall score is 0 and worst 10 points, that is zero moves away from the optimal, or a maximum of 10 errors or incorrect movements.

The qualitative scoring system along with SLS task had shown good to excellent intra and inter tester reliability (k=0.61 to 0.80, 73-87% agreement) on 34 healthy adults with a mean age of 24 years old (Crossley 2011; Whatman 2013). Furthermore, Almangoush et al. (2014) reported good to excellent inter-observer reliability (PA=83-100% with k=0.63-1.0) and intra-observer reliability (PA= 95%-100% with k=0.89-1.0) of a qualitative scale of the limb alignment during the SLS test (QASLS) on four health subjects (M=2, F=2).

Table 3. Qualitative analysis of single leg squat (QASLS)

QASLS	**Single leg squat**	**Score**	
		Left	Right
Arm strategy	Excessive arm movement to balance		
Trunk alignment	Leaning to 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	Patellar pointing towards 2nd toe (noticeable valgus)		
	Patellar pointing past inside of foot (significant valgus)		
Steady stance	Touches down with NWB foot		
	Stance leg wobbles noticeably		
	Total score		

Table 4: QASLS Optimal and suboptimal SLS task

QASLS category	Error	Optimal	Sub-Optimal example
Arm strategy	Excessive arm movement to balance		
Trunk alignment	Leaning in any direction		  
Pelvic Plane	Loss of horizontal plane		 
	Excessive tilt or rotation		
Thigh motion	WB thigh moves into hip adduction		  
Knee position	Patella pointing towards 2nd toe (Noticeable valgus)		 
	Patella pointing past inside of foot (Significant Valgus)		 
Steady stance	Touches down with NWB foot		
	Stance leg wobbles noticeably		

Frontal Plane Projection Angle (FPPA)

Frontal plane projection angle of the subject's knee was subtended between the line from the markers on the proximal thigh to the knee joint and the line from the knee joint to the ankle (Willson et al. 2006). The subject's knee abduction angle was captured at the point which corresponded to the lowest point of the landing during SLHD or squat descent phase. The lowest point of descent during SLHD was determined by visual observation of the distance of the hip (ASIS) to the floor during slow-motion capture by 2D motion analysis in the frontal plane. Positive FPPA values reflected knee valgus, excursion of the knee towards the midline of the body so that the knee marker was medial to the line between the ankle and thigh markers (Figure 2). Negative FPPA values reflected knee varus, excursion of the knee away from the midline of the body, average FPPA from three trials used for analysis. High reliability of within-day (ICC=0.86, SEM=2.9°, SDD=8.3°) and between days (ICC=0.81, SEM=3.4° and SDD=9.4°) of SLS with 2D FPPA has reported by Munro et al. (2013) in 10 healthy recreational men. The same examiner obtained FPPA in all studies for ACLD subjects, the control group, and following ACLR at three and six months in this thesis.

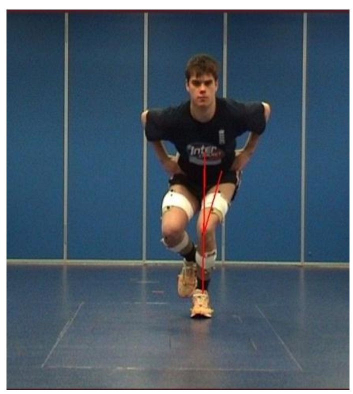

Figure 2: Frontal Plane Projection Angle during single leg squat.

Single Leg Hop Test (SLHT)

The single leg hop for distance, triple hop for distance, crossover hop for distance and six-meter timed hop tests initially described by Noyes et al., (1991). High reliability of single leg hop test for distance (ICC= 0.97) has reported by Munro and Herrington (2011). Participants performed four experimental trials of single leg hop for a distance until they got comfortable with the hop test followed by three final trials measured. The non-injured limb tested first, followed by the injured limb. All participants were advised to maintain hands on hips during the SLHD task to avoid any excessive force that might be produced from swinging the arms (Harman et al., 1990). Further, keeping the hands-on-hips reduces arm motion to reflect better lower limb performance (Impellizzeri et al., 2007). A rest period of 30 seconds given between trials and two minutes between each test was allowed (Reid et al. 2007). Each hop test began with the great toe of the testing leg on the marked start line, and the distance hopped was measured to the heal of the same foot upon final landing. Participants were required to maintain the final landing in the single-leg hop for the distance test for a minimum of three seconds. Unsuccessful SLHD was including a loss of balance, an extra hop on landing or touching down of either the contralateral lower extremity or the upper extremity and removing hands from hips.

For the single hop, participants required to hop as far forwards as possible along the line of the tape measure and land on the same limb. Leg length was measured from the anterior superior iliac spine to the distal tip of the medial malleolus using a standard tape measure while participants lay supine (Gribble & Hertel, 2003). Normalisation of data to leg-length was performed for YBT and SLHD test trials (Pincivero et al. 1997): per cent leg-length (%) = (distance hopped (cm) ÷ leg-length (cm) x 100. The mean normalised values for each leg for YBT and SLHD tests used for all analyses. LSI was calculated by dividing the normalise distance hopped on the injured limb by the non-injured limb multiplying the result by 100, giving a percentage value.

Y Balance Anterior Reach (ANT)

The Y Balance Test anterior reach (ANT) was assessed on the ACLD patients. Participants were instructed to perform the ANT using a combination of verbal cues and demonstration (Plisky et al. 2009). All Participants undertook the testing barefoot, with foot position controlled by aligning the heel with the centre of the grid and great toe with the anteriorly projected line. The participants were asked to perform a single-limb stance on the extremity while reaching outside the base of support to push a reach indicator box along the measurement pipe of the Y Balance Test Kit (Perform Better, West Warwick, RI). Leg length was measured from the anterior superior iliac spine to the distal tip of the medial malleolus using a standard tape measure while participants lie supine. The normalised composite reach distance, expressed as a per cent of leg length, is calculated by averaging the maximum reach in each of the three reach directions, dividing this number by three times leg length (Plisky et al. 2006).

Elevation of the heel or loss of balance was recorded as a trial error indicating the trial should then be repeated (Plisky et al., 2009). Participants were allowed at least three practice trials in the ANT direction before recording the best of three formal tests. Three trials were completed on the non-injured limb in the ANT direction followed by three trials conducted on the injured limb, and the maximal reach distance was recorded at the place where the most distal part of the foot reached based on the measurement pipe (Plisky et al., 2009).

Isokinetic knee strength test

Muscular strength was tested with an isokinetic device (Biodex System 3; Biodex Medical Systems, Inc, Shirley, NY). Relative and absolute reliability reported for peak torque and work variables on healthy patients with the mode of concentric and eccentric contractions for knee flexors and extensors for the velocities of 60º/s, 120º/s and 180º/s have been reported (Impellizzeri et al., 2008; Sole et al., 2007). In the current study, the absolute values were normalised to body mass ($N.m.kg^{-1}$) for an isokinetic test at a velocity of 60°/s (Sole et al., 2007). Further, the speed of 60°/s was utilised for the ACLD, ACLR group at three and six months postoperatively and the control group.

The recommended cut off values for normalised peak torque during isokinetic knee flexors, and extensor has been set at >3.0 ($N.m.kg^{-1}$) (Pietrosimone et al. 2016). The LSI was calculated between ACLD and a control group with cut off values of >90% (Munro and Herrington 2011). Peak torque has been used during isokinetic testing in the present study. Peak torque is a measure of the maximal torque exerted during knee extension and flexion; peak torque is a good measure of maximal strength (Maffiuletti et al. 2007). Torque output decreases as angular velocity increase above 60°/s, and the maximum torque output are shown between 0-60°/s (Baltzopoulos and Brodie 1989). Therefore, it is imperative to utilise an angular velocity of 60°/s that will consistently highlight strength deficiency.

Subjects performed five consecutive submaximal concentric and eccentric contractions as a specific warm-up and became familiar with the movement. There was a 1-minute break between the warm-up and the testing. The subject of the current study performed five repetitions of the concentric and eccentric maximum knee extensions and flexions at 60°/s with 30 seconds rest.

Five maximal repetitions are used in the current study because peak torque is achieved within four repetitions (Kannus and Kaplan 1988). By utilising five repetitions, there is a greater chance of recording the highest peak torque and less chance of fatigue (Undheim et al. 2015)

To reduce examiner variability, the same investigator (MK) conducted the tests for all subjects on both groups. ACLD subjects were informed about aborting the test if they felt any discomfort or pain. During the isokinetic testing, all participants were given visual feedback from the system's monitor. They were also verbally encouraged by the investigator to provide their maximal effort.

Subjects were instructed to extend the knee against the shin pad during concentric extensions and to resist the lever during eccentric extension. The dynamometer was set for knee flexion. Subjects were instructed to flex the knee during concentric flexion and to resist the dynamometer during eccentric flexion. Total knee motion has been set at 80º (10°-90° knee flexion) to avoid inertial artefacts due to acceleration and deceleration periods of the movement. Also, the inertial forces during dynamic activations ("torque overshoot") affect the reliability and validity of isokinetic measurements (Sapega et al., 1982). Thereby allowing the subject 10° movement at each end of the knee range of motion for acceleration and tension development, and to remove from the torque record (refer to chapter 2 for more details) (Kellis, Baltzopoulos 1996). In the current study, the method of Nelson and Duncan (1983) has been used for gravity correction in 30º knee flexion from a static position to reduce hamstring tension (Fitzgerland et al., 1991; Westing, Seger 1989).

Subjects were positioned on an adjustable chair and secured to the equipment with straps across the trunk, hip and thigh. The alignment between the dynamometer rotational axis and the knee joint rotation axis (lateral femoral epicondyle) was checked at the beginning of each trial. The shin pad was attached about 5 cm proximal to the lateral malleolus by using a strap. The participants were asked to position their arms across the chest with each hand clasping the opposite shoulder during the maximal effort trials.

Statistics

A post hoc power analysis (*G* Power, Version 3.1.7) with mean differences between two dependent means with existence of the sample sizes for the ACLD and control group were used to understand the level of statistical power of an observed effect based on the sample size (Buchner et al. .2019). Power calculation for each individual outcome variables found it in table 8. The mean LSI values for Y balance test, isokinetic knee strength test, SLS, and SLHD were measured for ACLD group and the control group Statistical analysis was performed in SPSS for Mac OS (IBM, New York, NY, USA). Normality of all data was inspected using a Shapiro–Wilks test. Independent t-tests were used for normally distributed data to compare the ACLD group and control group. Mann Whitney U tests were performed for a non-normally distributed data to compare ACLD group and control group in terms of distance (YBT, SLHD), strength, KOOS, TSK and 2D FPPA during tasks (SLHD and SLS). Alpha was set for 0.05. Paired t-tests were used to compare between injured limb versus non-injured limb, injured limb versus dominant limb of the control group and non-injured limb versus control limb mean values (Barber et al., 1990; Clark, 2001). Bonferroni-corrected was used to reduce the likelihood of type 1 error. For each individual test Bonferroni-corrected alpha was set at 0.002 (Alpha level (0.05) x three limbs (injured limb versus non-injured limb, injured limb versus control limb and non-injured limb versus control limb) x 10 quantitative tests) for each individual task comparison (Portney & Watkins, 2009; Stovitz et al. 2017). Also, 95% confidence intervals (CI) with lower bound and upper bound were calculated for ACLD and control group between injured limb, non-injured limb and control limb values (Dankel et al., 2017; Gardner & Altman, 1986; Stovitz et al., 2017). Cohen's d (ES) was calculated (mean 1- mean 2/SD pooled) between ACLD and control group limbs (Portney & Watkins, 2009). Effect sizes of 0.20, 0.50, and 0.80 were considered small, medium, and large, respectively (Portney & Watkins, 2009).

Result:

No subjects for ACLD and control group experienced pain during testing, and there were no adverse events. All data were normally distributed (P>0.05). Good power was observed during the YBT (injured versus control limb), SLHD (injured versus control limb), QASLS, QASLH, PTQC, PTQE, PTHE and KOOS/QOL (Table 7). Low power was observed during the YBT (injured versus non-injured limb and non-injured versus control limb), SLHD (injured versus non-injured limb and non-injured versus control limb), FPSLS, FPSLH, QASLS (non-injured versus control limb), QASLH (injured versus non-injured), PTHC, KOOS and TSK (Table 7). There were no significant side to side difference (p>0.002) for the YBT, SLHD, 2D FPPA for SLS and SLHD, QASLS for SLS and SLHD (Table 7). Also, there was no significant side to side difference (p>0.002) for the normalized peak torque hamstring concentric contraction, KOOS/symptoms and KOOS/ADL (ACLD groups to control group) (Table 7).

There was a significant side to side difference ($p<0.002$) for the normalized peak torque for concentric contraction of quadriceps and eccentric contractions for quadriceps and hamstring muscle, KOOS/pain, KOOS/sport, KOOS/QOL and TSK (Table 7). The YBT, 2D FPPAº (SLS and SLHD), normalized peak torque concentric contraction of hamstring, KOOS/sport and KOOS/ADL tests injured, non-injured and control limb mean values and 95% CI were small with small ES (Table 5-7). The 95% CI was quite different with a medium ES for the QASLS (SLS and SLHD), normalized peak torque concentric contraction for quadriceps and eccentric contractions for hamstring and quadriceps muscles, KOOS/pain, and KOOS/sport tests for the ACLD and control group (Table 5-7). The KOOS/QOL and TSK test between ACLD and control group tests mean values and 95% CI were quite different with large ES (Table 6-7). The LSI for YBT (injured limb to control limb), SLHD, normalized peak torque concentric contraction for hamstring and quadriceps muscles (injured limb to non-injured limb), normalized peak torque eccentric contraction for hamstring muscle (injured limb to non-injured limb), and KOOS (pain and sport) were below 90% cut off values (Table 8-9).

Table 5: Mean, standard deviation (SD) and 95% confidence interval between ACLD subjects (injured limb to non-injured) and dominant side of control group for YBT, SLHD, 2D FPPAº (SLS and SLHD), QASLS (SLS and SLHD) and normalised peak torque ($N.m.kg^{-1}$) for quadriceps and hamstring muscles tasks. The distance hopped was normalized to a percentage of leg length (distance from anterior superior iliac spine to medial malleolus) and multiplying by 100.

	Mean			SD			95% CI		
	IN	NI	CTRL	IN	NI	CTRL	IN	NI	CTRL
YBT (%)	60.69	62.09	67.49	6.90	7.36	6.05	57.1-64.2	58.3-65.9	65.1-69.8
SLHD (%)	84.91	105.09	118.01	33.07	33.68	26.61	67.9-101.9	87.7-122.4	118.1-121.9
FPSLS º	16	16	17	5	4	3	15 -18	15 -17	16 -19
FPSLHD º	17	16	17	4	5	3	15 -18	14-17	16–18
QLSLS	5	4	4	1	1	1	4.7 - 5.2	4.3 - 5.9	3.3-4.7
QLSLHD	5	5	4	1	1	1	4.9- 5.3	4.9- 5.3	4.4- 5.1
PTQC ($N.m.kg^{-1}$)	2.69	3.84	1.57	1.37	1.50	0.43	1.9-3.3	3.0-4.6	1.3-1.7
PTQE ($N.m.kg^{-1}$)	4.00	5.15	1.51	1.79	2.06	0.53	3.0-4.9	4.0-6.2	1.2-1.7
PTHC ($N.m.kg^{-1}$)	2.17	2.73	1.64	1.12	1.37	0.29	1.5-2.7	2.0-3.4	1.5-1.7
PTHE ($N.m.kg^{-1}$)	2.82	3.51	1.77	1.04	1.30	0.43	2.2-3.3	2.8-4.1	1.5-1.9

Percentage of leg length (LL%) = (distance hopped (cm) ÷ leg-length (cm) x 100.; 2D frontal plane projection angle for single leg squat (FPSLSº) and single leg hop for distance (FPSLHDº), Qualitative analysis for single leg squat (QSLS) and single leg hop for distance (QSLHD); Injured limb (IN); Non-injured limb (NI); control limb (CTRL) and Standard deviation (SD). 95% confidence interval (CI); Normalised peak torque quadriceps concentric contraction (PTQC); Normalised peak torque quadriceps eccentric contraction (PTQE); Normalised peak torque hamstring concentric contraction (PTHC); Normalised peak torque hamstring eccentric contraction (PTHC).

Table 6. Mean, Standard deviation (SD) and 95% confidence interval between ACLD and control group for KOOS and TSK.

	KOOS-Pain		KOOS-Symptoms		KOOS-ADL		KOOS-Sport		KOOS-QOL		TSK	
	ACLD	CTRL	ACLD	CTRL	ACLD	CTRL	ACLD	CTRL	ACLD	CTRL	ACLD	CTRL
Mean	82.13	92.59	68.68	65.85	86.77	94.37	68.52	88.70	61.63	86.48	39.20	35.19
SD	19.2	10.20	13.03	6.96	16.57	8.17	33.07	14.58	35.87	12.67	6.86	4.52
95% CI	76.2- 87.9	88.5-96.6	64.7-72.6	63.0-68.6	81.7- 91.8	91.1- 97.6	58.4- 78.5	82.9-94.4	50.7- 72.5	81.4-91.4	37.1-41.2	33.3-36.9

KOOS-Pain= knee osteoarthritis outcome score for the pain subscale; KOOS-symptoms= knee osteoarthritis outcome score for the symptom's subscale; KOOS-ADL= knee osteoarthritis outcome score for the activity daily living; KOOS-sport= knee osteoarthritis outcome score for sport; KOOS-QOL= knee osteoarthritis outcome score for the quality of life; TSK=Tampa scale kinesiophobia

Table 7: Mean pairwise comparison between ACLD and control group

Variables	P values	ES	Power (1-β err prob)
ANTRIN versus ANTRNI	.91	.39	.11
ANTRIN versus ANTCTRL	.17	.39	.91
ANTRNI versus ANTRCTRL	.68	.39	.71
SLHIN versus SLHNI	.30	.50	.64
SLHIN versus SLHCTRL	.08	.50	.93
SLHNI versus SLHCTRL	.50	.50	.26
FPSLSIN versus FPSLSNI	1.00	.18	.05
FPSLSIN versus FPSLSCTRL	.78	.18	.14
FPSLSNI versus FPSLSCTRL	.23	.18	.25
FPSLHIN versus FPSLHNI	.92	.24	.11
FPSLHIN versus FPSLHCTRL	1.00	.24	.10
FPSLHNI versus FPSLHCTRL	.12	.24	.24
QSLSIN versus QSLSNI	.32	.62	.97
QSLSIN versus QSLSCTRL	.01	.62	.88
QSLSNI versus QSLSCTRL	1.00	.62	.05
QSLHIN versus QSLHNI	.01	.60	.05
QSLHIN versus QSLHCTRL	.08	.60	.88
QSLHNI versus QSLHCTRL	1.00	.60	.88
PTQCIN versus PTQCNI	.003	.71	.87
PTQCIN versus PTQCTRL	.02	.71	.93
PTQCNI versus PTQCTRL	.001	.71	.99
PTQEIN versus PTQENI	.001	.74	.63
PTQEIN versus PTQECTRL	.04	.74	.99
PTQENI versus PTQECTRL	.0001	.74	1.00
PTHCIN versus PTHCNI	.046	.42	.40
PTHCIN versus PTHCTRL	.30	.42	.53
PTHCNI versus PTHCTRL	.019	.42	.93
PTHEIN versus PTHENI	.009	.61	.61
PTHEIN versus PTHECTRL	.007	.61	.98
PTHENI versus PTHECTRL	.001	.61	.99
KOOSP versus KOOSCTRL	.001	.53	.57
KOOS/Symptoms versus KOOSCTRL	.20	.09	.13
KOOS/ADL versus KOOSCTRL	.003	.43	.45
KOOS/Sport versus KOOSCTRL	.001	.68	.70
KOOS/QOL versus KOOSCTRL	.001	.86	.83
TSK versus TSKCTRL	.001	.83	.58

ANTRIN=anterior reach balance test injured limb(ANTRIN); ANTRNI= anterior reach balance test non-injured limb; ANTRCTRL= anterior reach balance test control group; ES= effect size; SLHIN=single leg hop distance injured limb; SLHNI= single leg hop distance non-injured limb; SLHCTRL= single leg hop distance control group; FPSLSIN°= 2D frontal plane projection angle for single leg squat injured limb; FPSLSNI°= 2D frontal plane projection angle for single leg squat non-injured limb; FPSLHIN°= 2D frontal plane projection angle for single leg hop injured limb; FPSLHNI°= 2D frontal plane projection angle for single leg hop non-injured limb; FPSLSCTRL°= 2D frontal plane projection angle for single leg hop control group; FPSLSCTRL°= 2D frontal plane projection angle for single leg squat control group; LSI= limb symmetry index; QASLSIN= Qualitative analysis single leg squat injured limb ; QASLSNI= Qualitative analysis single leg squat non-injured limb; QASLSCTRL= Qualitative analysis single leg squat control group; QASLHIN= Qualitative analysis single leg hop injured limb; QASLHNI= Qualitative analysis single leg hop non-injured limb; QASLHCTRL= Qualitative analysis single leg hop control group; PTQCI=Normalised peak torque quadriceps concentric contraction injured limb; PTQCNI=Normalised peak torque quadriceps concentric contraction non-injured limb; PTQCTRL=Normalised peak torque quadriceps concentric contraction control group; PTQEI= Normalised peak torque quadriceps eccentric contraction injured limb; PTQENI= Normalised peak torque quadriceps eccentric contraction non-injured limb; PTQECTRL= Normalised peak torque quadriceps eccentric contraction control group; PTHCI= Normalised peak torque hamstring concentric contraction injured limb; PTHCNI= Normalised peak torque hamstring concentric contraction non-injured limb; PTHCTRL= Normalised peak torque hamstring concentric contraction control group; PTHEI= Normalised peak torque hamstring eccentric contraction injured limb; PTHENI= Normalised peak torque hamstring eccentric contraction non-injured limb; PTHECTRL= Normalised peak torque hamstring eccentric contraction control group; KOOSCTRL= KOOS control group and TSKCTRL= TSK control group.

Table 8. The mean pairwise LSI comparison between ACLD and control group.

Variables	ACLDIN versus ACLDNI	ACLDIN versus CTRL	ACLDNI versus CTRL
YBT	**97.7**	**89.92**	**91.99**
SLHD	**80.79**	**71.95**	**89.05**
FPSLS	**101.5**	**93.81**	**92.41**
FPSLHD	**105.2**	**96.17**	**91.35**
QASLS	**125.1**	**125.6**	**100.1**
QASLHD	**100.2**	**125**	**125**
PTQC	**70.05**	**171**	**244**
PTQE	**77.6**	**264.2**	**341.05**
PTHC	**79.48**	**132.3**	**166.4**
PTHE	**80.3**	**159.3**	**198.3**

YBT= Y balance test; SLHD= single leg hop for distance; 2D frontal plane projection angle for single leg squat (FPSLSº) and single leg hop for distance (FPSLHDº), Qualitative analysis for single leg squat (QSLS) and single leg hop for distance (QSLHD); Injured limb (IN); Non-injured limb (NI); control limb (CTRL); Normalised peak torque quadriceps concentric contraction (PTQC); Normalised peak torque quadriceps eccentric contraction (PTQE); Normalised peak torque hamstring concentric contraction (PTHC); Normalised peak torque hamstring eccentric contraction (PTHC).

Table 9. The mean LSI of the KOOS and TSK subjective questionnaires between ACLD and control group.

Variables	ACLD versus CTRL
KOOSP	**88.07**
KOOS/symptoms	**104**
KOOS/ADL	**91.94**
KOOS/Sport	**77.24**
KOOS/QOL	**71.26**
TSK	**111**

KOOS-Pain= knee osteoarthritis outcome score for the pain subscale; KOOS-symptoms= knee osteoarthritis outcome score for the symptom's subscale; KOOS-ADL= knee osteoarthritis outcome score for the activity daily living; KOOS-sport= knee osteoarthritis outcome score for sport; KOOS-QOL= knee osteoarthritis outcome score for the quality of life; TSK=Tampa scale kinesiophobia

Discussion

Traditionally, after ACL injuries, the non-injured limb would be used as a reference limb for comparison after ACLR surgery. The limb symmetry indices are calculated between the involved and uninvolved limb for strength testing, a battery of hop tests and quality of unilateral movements during SLS and SLHD to determine readiness to return (Hannon et al. 2017). The purpose of this study to assess KOOS, TSK, isokinetic knee flexor and extensor, YBT, and 2D FPPA during SLS and SLHD tests between ACLD and the control group comparing injured to non-injured limb, injured to control limb and non-injured to control limb. It was hypothesised that the control limb would perform better than the ACLD group for both the injured and non-injured limb. The findings of the current study demonstrate there was no side to side (injured to non-injured limb) significant differences in the YBT, SLHD,2D FPPA for SLS and SLHD, QASLS for SLS and SLHD tasks. Further, there was no side to side differences in the normalised hamstring peak torque for concentric contractions, and KOOS (symptoms and ADL) tests when compared the ACLD limbs to the control limb (Table 5-7). Other findings demonstrated there was side to side significant differences in the normalised peak torque for eccentric hamstring contraction, concentric and eccentric contraction for quadriceps, KOOS (QOL, pain, sport) and TSK tests when compared between ACLD and control limbs (Table 5-7). The control group performed better in all tests except for isokinetic knee strength (normalised peak torque for hamstring and quadriceps (Table 5) and QASLS (SLHD) tests (Table 5) compared to both limbs in ACLD group.

Comparison of the present data (Table 5-9) to previous literature is not possible because no other work has reported such data (KOOS, TSK, YBT, isokinetic knee strength test, 2D FPPA for two tasks (SLS and SLHD) and QASLS during (SLS and SLHD) for an adult male from United Arab of Emirates. The alternative is to compare the present data (Table 5-9) to values reported for other adult male athletes and recreational athletes and mixed sex adult groups.

Herrington et al. (2009) reported the ACLD patients (m=17, f=8 with a mean age of 30) had bilateral deficit compared to twenty -five matched control group. Herrington et al. (2009) reported four directions (anterior, medial, posterior medial, and lateral) deficit in the injured limb and two directions (medial and lateral) deficit during SEBT. Earl et al. (2001) reported significant increase in Electromyography (EMG) activity of quadriceps during anterior reach balance test, and the distance has a moderate correlation to concentric strength of the quadriceps activity (Thorpe and Ebersole 2008).

Thorpe and Ebersole (2008) stated that the symmetry of reach during YBT providing a good indicator of quadriceps function. In the current study symmetry of anterior reach has reported between injured to the non-injured limb (LSI=97.7%) and non-injured to control limb with LSI value of 91.99% and asymmetry has reported between injured to control limb with LSI value of 89.92% (Table 8). However, in the current study the mean LSI peak torque of quadriceps has reported significant differences between the injured limb and non-injured limb in the mode of concentric (LSI=70.05%), and eccentric (LSI=77.6%) contractions (Table 8), so this question the sensitivity of anterior reach to detect significant strength deficits.

Contrary to our findings in the ACLD knee, Herrington et al. (2009) reported a significant difference between the control group and ACLD knee in four directions (anterior, medial, lateral and posterior-medial reach directions). Furthermore, Herrington et al. (2009) revealed that a deficit also exists in the non-injured side compared to controls for medial and lateral reach directions. From comparison point of view between our study and Herrington et al. (2009) study, in the present study, the time since an injury to perform YBT was four weeks in comparison to mean of 11 months by Herrington et al. (2009). Also, the patients in our study had regular physiotherapy and rehabilitation sessions before testing. Therefore, the sample of our research has shown no deficit in YBT balance test.

Furthermore, from the sex point of view, Herrington et al. (2009) used mixed sex, which, may skew the result compared to our study that the YBT performed on male patients only. Lastly, in the current study, LSI quadriceps deficit in both mode of concentric and eccentric contractions is reported. Still, there were no significant differences between ACLD group to control group with low power <0.80, small ES (0.39), and similar 95% CI (Table 5&8) were reported for YBT, suggesting there is no real differences exist in YBT performance. Also, the finding of the YBT in the current study indicate that the investigation had insufficient power to produce a significant result. Observed power is an estimate of the power based on the observed effect size in a study. However, because the other parameters such as sample size and significance criterion that are needed to compute power, the observed effect size is the only parameter that needs to be observed to estimate power. But, observed power is still an estimate based on an observed effect size because power depends on the effect size in the population and observed effect size in a sample is just an estimate of the population effect size (Yuan and Maxwell 2005). Therefore, the use of ES alongside P- values are advocated because P-values alone do not indicate the magnitude of difference between two central tendencies for the same variable (Stovitz et al., 2017). Use of the 95% CI is advocated because effect size distorts study findings and be misleading (Dankel et al. 2017). Therefore, test-retest reliability alongside SEM and SDD is required to discover the true clinical meaningful of individual interventions in the current study.

Thorpe and Ebersole et al. (2008) reported symmetrical reach balance in anterior, posterior and medial directions with moderate correlation in normalised quadriceps peak torque 60º/s with the mode of concentric contraction only on 23 healthy female soccer players. Therefore, in the current study, there appears to be no relationship between symmetrical anterior reach balance and peak torque quadriceps in the mode of concentric and eccentric contractions. These are differences in sample characteristics; perform the SEBT and YBT at difference timing, mixed results data of male and female, and difference activity level of samples that may relate to the different statistical findings.

In the systematic review in chapter 2 three studies by Xergia et al. (2013); Ithurburn et al. (2017) and Gokeler et al. (2017) reported on the quality of single leg hop distance during landing to measure kinematic differences, propulsion and landing phase on patients following ACLR at 6 and 12 months (Xergia et al. 2013; Gokeler et al. 2017) and 7 and 24 months (Ithurburn et al. 2017).

To date, there is no published study measuring the quality of landing during single leg hop for distance in ACLD patients. It would appear essential to compare the quality of landing between injured to non-injured limb, injured to control limb and non-injured limb to control limb of ACLD and control group alongside the absolute distance hopped. After ACL injury, the non-injured limb shown 25.5% quadriceps deficit after 23 days (Hannon et al. 2017). Therefore, utilising non-injured limb as a reference limb for side to side comparison should take a careful consideration after an ACL injury to predict and assess the outcome measures following ACLR at three and six months.

Studies by Rohman et al. (2015) and Hall et al. (2015) reported on SLS following ACLR. Rohman et al. (2015) examined 38 patients following ACLR at both 4, and six months postoperatively with a mean age of 26 years old. Hall et al. (2015) examined thirty-three patients who underwent ACLR at six months postoperatively with mean age 15-50 years old. Finding by Hall et al. (2015) showing 45% (15 of 33 patients) of the patients demonstrated poor performance with decreased hip abduction strength on an operated limb, lower IKDC and SLHD of the operative limb. Rohman et al. (2015) and Hall et al. (2015) did not measure 2D FPPA for SLS to assess peak knee valgus following ACLR along with QASLS score sheet to determine optimal and suboptimal movement pattern. An alternate explanation for the symmetrical 2D FPPA changes in the ACLD subjects during SLS and SLHD may be that the injury itself has caused bilateral neuromuscular deficits. Further, both the control and ACLD group have shown knee valgus during SLS and SLHD but with low power <0.80, small ES (SLS=0.18 and SLHD=0.24) and similar 95% CI for ACLD and control limb group (Table 5 & 8). Therefore, 2D FPPA during two tasks (SLS and SLHD) were symmetrical between ACLD and control limbs. Because, the ACLD group had a regular physiotherapy and rehabilitation program to restore knee range of motion, this may have led to an improved movement quality during bilateral and unilateral tasks and improved quadriceps strength before ACLR surgery.

Studies by Urbach et al. (1999) and Konishi et al. (2003) found a bilateral deficit in quadriceps performance of ACLD patients. Hannon et al. (2017) reported on thirty- one (m=19, f=12) subjects with 25.5% quadriceps deficit in the un-involved ACLD knee after 23 days of ACL injury. If rupture to the ACL causes bilateral quadriceps deficit (Urbach et al., 1999; Konish et al., 2003; Hannon et al., 2017), the result of the current study for 2D FPPA during SLS and SLHD indicate these differences are not related to quadriceps weakness or activation. The most ACL injuries occur during the frontal and transverse plane of motions (Earl et al., 2005). Furthermore, an athlete has to move in multiple directions as quickly as possible during pivoting sports activities (Itoh et al. 1998). In the current study, the goal of 2D FFPA during two tasks (SLS and SLHD) to quantify the magnitude of knee valgus on ACLD knee. However, both McLean et al. (2005) and Willson and Davis (2008) stated the lack of sensitivity of 2D FPPA to measure subtle changes in knee angle may impact on the sensitivity of the test. Willson and Davis (2008) found 2D knee valgus reflected 23% to 30% of the variance of 3D measurements during SLS. Studies by McLean et al., (2005) and Wilson and Davis (2008) agreed with the current research which identified significant differences between injured and non-injured ACLD knee. Therefore, this subtle observation might not be identified by 2D FPPA during SLS and SLHD, but could be clarified, relative and absolute reliability were known so meaningful change could be identified.

The result of the study indicates that there was a bilateral peak torque quadriceps and hamstring deficit between injured and non-injured limb in ACLD group ranges from LSI= 70.5%- 80.3% (Table 9). This study found, there was a statistically significant side to side differences between ACLD and dominant side of the control group with good power >0.80, medium to large ES (.42-.74) with quite different 95% confidence interval (Table 5 & 8). Finding of the current study, suggesting there were, in fact, the real performance differences exist between the ACLD and control group. However, the finding of the present study showed more quadriceps, and hamstring deficit in the control group ranges from (PTQ= 1.51-1.57 $N.m.kg^{-1}$ and PTH=1.64-1.77 $N.m.kg^{-1}$) compared to the ACLD group (Table 5) which, was not aligned with the hypothesised of the study. The subjects of the control group did not have a regular rehabilitation (strength training) exercise session with Biodex compared to the ACLD group, so the ACLD could have become stronger because of the intervention relative to the control group or more familiar with the Biodex hence performing better on testing. The ACLD group had six sessions of physiotherapy per week to regain knee range of motion, muscular strength (Biodex 3 sessions a week), neuromuscular control and cardiovascular exercises before ACLR surgery. The control group in the current study were professional athletes with lower body mass and height compared to the ACLD group (Table 1). Perhaps the control group's lower body mass and height could produce lower quadriceps and hamstring peak torque compared to the ACLD group. Also, performing isokinetic knee flexor and extensor contractions consistently and maximally was difficult to achieve for the control group without regular use of the Biodex isokinetic dynamometer giving them a degree of familiarisation, which the ACLR group had as they exercised on the dynamometer as well as were tested on it.

The implication of having decreased quadriceps strength in this ACLD-pre-op group was identified in a study by Ueda et al. (2017) reported the cutoff value of 70.2%, sensitivity 69.1%, specificity 61.5% and Area under the Curve (AUC) value 0.65 for pre-operative quadriceps strength index in 193 athletes with isokinetic quadriceps strength at 60°/s to obtain at least 85% quadriceps strength index six months after surgery. Eitzen et al. (2009) found that patient (male=47 and female=26) with pre-operative quadriceps strength deficit more significant than 20% had significantly lower quadriceps strength two years after ACLR. However, in the recent study by Hannon et al. (2017) found 25.5% quadriceps deficit in the non-injured leg of ACLD patients 23 days after the injury. These particular quadriceps muscle weakness in the non-injured side are in agreement with studies (Urbach et al., 2001 and Urbach and Awiszus 2002). The cutoff value by Ueda et al. (2017) shown moderate sensitivity, with a mix of population and sport types are leading to potential flaw and confounding outcomes.

Furthermore, focusing only on knee muscle strength and non-injured limb as a reference limb at the pre-operative phase will lead to poor outcome following ACLR. These cutoff values from studies by Urbach et al., (2001); Urbach and Awizsus (2002); Eitzen et al. (2009); Ueda et al., (2017) and Hannon et al. (2017) agreed with present study with relation to significant quadriceps deficit on both limbs.

Therefore, regular pre-operative rehabilitation exercise is required to achieve quadriceps and hamstring symmetry along with full knee range of motion before ACLR surgery. Also, relative and absolute reliability of isokinetic knee flexors and extensors with the mode of concentric and eccentric contractions are required to discover the true meaningful differences between limbs.

In the present investigation, there were no significant difference (P>0.002) in QASLS score for SLS between injured to non-injured to control limb. However, considering the power & ES, there was good power >0.80, medium ES (.62) (Table 5, 7) during SLS. Therefore, in the current study, the QASLS score during SLS between injured to non-injured limb to control limb has the potential to be different, especially if greater numbers were assessed. There were no significant side to side differences (P>0.002) between ACLD and control group for QASLS score during SLHD with good power and medium ES (.60) but similar 95% confidence interval, suggesting there were no real differences between the ACLD, and control group exist. The qualitative scoring system used (QASLS) has been shown to have excellent validity when compared to 3D motion capture kinematics during single leg squatting and landing (Alenezi et al. 2014), excellent intra and inter-tester reliability (Almangoush, Herrington, & Jones, 2014). Compared to the 2D FPPA, visual assessment (QASLS) has the potential to be a better tool to predict outcome measures following ACLR at three and six months. Two-dimensional FPPA video analysis has been considered as a useful method for measuring knee valgus during functional movement tasks (Herrington 2013; McLean et al., 2005; Ekegren et al., 2009; Mizner et al., 2012; Munro et al., 2012; Stensrud et al., 2011; Willson and Davis 2008). However, focusing only on the knee joint in the current study as FPPA does, and neglecting the arm, trunk, hip, foot, and ankle movement patterns may have led to it being poorer outcome measurement. In contrast to the present study where whole-body movement pattern is assessed during SLS and SLHD with the visual observation (QASLS) (Mizner et al., 2012; Crossley et al., 2011 and Whatman et al., 2013), the QASLS has not yet been measured with 2D video analysis in the ACLD male patients. The QASLS used in the current study in ACLD patients found increased lateral displacement of the trunk in the frontal and transverse plane of motion, this lateral leaning could create more ground reaction vector to the lateral knee joint, thereby increasing the knee valgus moment. Dingenen et al. (2014) reported excellent intraclass correlation coefficients for the lateral trunk movement angle found within (0.99-1.00) and between testers (0.98-0.99). Furthermore, Dingenen et al. (2014) found the mean of knee valgus and lateral trunk movement significantly correlated with the peak knee valgus during the single-leg vertical jump in 43 healthy females.

During SLS and SLHD tasks, optimal neuromuscular control of the hip and trunk needed to control the position and motion of the trunk over the pelvis to allow optimal production, transfer and control of the force and move to more distal segments of the kinetic chain (Kibler and Sciascia 2006). Therefore, it's imperative to identifying suboptimal full-body movement pattern in the ACLD patients rather than only focusing on the knee joint, hence using the QASLS score has potential value.

There are potential limitations these include not performing dominant to non-dominant side to comparisons in the control group (Barber et al., 1990; Hewit et al., 2012). Bussey (2010) and McGrath et al. (2016) stated that such a comparison not performed because dominance/preference changes are related to task demands (e.g., skill, load-bearing). Therefore, the dominant side for the control group defined as the limb the subject reported to kick a ball with during football game and to land with left leg during overhead sports (volleyball, basketball and handball) (Table 1). Potential limitations also include using a 2D FPPA during SLS and SLHD. Both McLean et al. (2005) and Willson and Davis (2008) stated the lack of sensitivity of 2D FPPA to measure subtle changes in knee angle. Willson and Davis (2008) found 2D knee valgus reflected 23% to 30% of the variance of 3D measurements during SLS.

But interestingly Willson and Davis (2008) found knee valgus significantly correlated with external knee (tibial) rotation (r=0.54, p=0.001) and hip adduction (r=0.32, p=0.04), which are a significant component of medial knee collapse 2D knee valgus angle which it aims to represent. Potential limitations also include using post hoc analysis instead of a priori analysis in the present study. When the data of current has analysed, there was a significant difference discovered between means of ACLD and control group with an existence sample size. Also, post hoc analysis was an essential procedure for multiple variables comparison testing to control type 1 error data and rendering the chance of discovering false positives unacceptably high. This study only generalised to an adult male from the Middle East region. Further research should replicate this study on professional athletes and even community level on adult females and children/adolescent females and an adult male.

Conclusion

The tests used in the current study were safely employed on both the ACLD and control group. There was no side to side significant differences in the YBT, SLHD, 2D FPPA for SLS and SLHD tasks, QASLS for SLS and SLHD, normalised hamstring peak torque for concentric contractions and KOOS (symptoms and ADL) tests for ACLD and control group. However, there was side to side significant different in the normalised peak torque hamstring with the mode of eccentric contraction, normalised peak torque quadriceps with the mode of concentric and eccentric contraction, KOOS (QOL, pain, sport) and TSK tests for the ACLD and control group. The control group showed greater quadriceps and hamstring deficit compared to the ACLD group, which may relate to the different training exposures of the two groups The ACLD group also showed bilateral quadriceps deficit after an ACL injury, compared to typical data from the literature. Performing pre-operative rehabilitation should be recommended for quadriceps strengthening on both the injured and non-injured limb. Also, restoring full knee range of motion and reducing the fear of movement during single-leg tasks starting from low load/impact with proper full-body movement alignment should be achieved to improve the confidence of athletes for faster recovery after ACLR surgery and RTS. But the rehabilitation process must be carefully monitored as despite completing a period of rehabilitation deficit still exist. Also using the LSI may underestimate performance deficit and should be used along with observed power, ES, 95% CI to discover true performances for each task as a criterion for RTS after ACLR.

Chapter four

Outcome from anterior cruciate ligament reconstruction (ACLR) at three and six months compared to matched controls

Summary

This chapter aimed to report a KOOS, TSK, YBT, isokinetic knee strength test, 2D FPPA during SLS and SLHD and QASLS during SLS and SLHD at three and six months following ACLR surgery. Further, to compare the result of the ACLR group at three and six months postoperatively to the control group of adult males from a Middle Eastern population. The findings of the current study demonstrated that the control group demonstrated better scores in the YBT, 2D FPPA and QASLS during SLS and SLHD and all subscales of KOOS than both limbs of the ACLR at three months. However, the control group demonstrated poorer results in the single leg hop for distance (LL%), normalised peak torque eccentric quadriceps and hamstring, concentric for hamstring and TSK compared to the ACLR at three months. Other findings demonstrated that the control limb had better scores in YBT, 2D FPPA during SLS and SLHD and all subscales of KOOS than both legs of the ACLR group at six months. But the control group showed the poorer results in the normalised peak toque in eccentric quadriceps, and hamstring muscles, SLHD, QASLS during SLS, KOOS/symptoms and TSK compared to the injured and non-injured limb of the ACLR at six months. Also, the ACLR injured limb at six months showed better scores in YBT, 2D FPPA and QASLS during SLS and SLHD. The ACLR group at six months had better scores in the normalised peak torque eccentric quadriceps, KOOS and TSK than the ACLR injured limb at three months. The 6-month scores were worse for the SLHD, normalised peak torque concentric quadriceps and hamstring concentric contraction of quadriceps and hamstring muscles and eccentric of the hamstring muscle than the ACLR group at three months.

Introduction

As discussed in chapter 1 and 2, injuries to the ACL are one of the most common and devastating sports injuries (Welling et al. 2019). ACL injuries are associated with long term poor clinical outcome, and concurrent comorbidities including meniscal tears, osteochondral lesions and post-traumatic osteoarthritis (PTOA) (Lohmander et al., 2007; Oiestad et al., 2013; Andernord et al. 2013). Among young and physically active populations, roughly 50% of ACL injuries progress to radiograph PTOA and meniscal tears within 12 years (Lohmander et al., 2007; Englund and Lohmander 2004). Of the young athletes (<25 years old) who do return to sport 1 in 4 are likely to experience a second ACL injury (Wiggins et al. 2016), and many of ACL injuries occur within 24 months of returning to sport (Rugg et al. 2014; Paterno et al. 2014). Surgical interventions are available to repair theses injuries and restore short-term (first year after injury) function and mobility potentially to pre-injury performance levels. Still, surgical repair does not prevent early development of PTOA in the knee joint (Chalmers et al. 2014).

Isokinetic strength testing is a reliable method to measure peak torque of knee extensors and flexors (Che, Wu, Maffuli, and Chan 1996; Impellizzeri, Bizzini, Rampinini, Cedera, and Maffiuletti 2008; Keskula, Dowling, Davis, Finley, and Dell'Omo 2008; Maffiuletti, Bizzini, Desbrosses, Babault, and Munzinger 2007; Sole, Hamre, Milosvljevi, Bicholson, and Sullivan 2007). Impellizzeri et al. (2008) established good to excellent ICCs (0.90-0.98) and the SEM (4.3%-7.7%) on eighteen healthy subjects with concentric and eccentric contractions of quadriceps and hamstring muscles. Also, Sole et al. (2007) established relative and absolute reliability (ICC>0.90 and SEM=5%-10%) on the healthy subjects (male=11 and female=7) with a velocity of 60°/s.

The inability to contract the quadriceps during both concentric and eccentric contractions is hypothesized to be a primary mechanism linking ACL injury and ACLR to atypical movement biomechanics after ACL injury and ACLR (Palmieri-Smith et al. 2009) which could then predispose the individual to osteoarthritis (Herrington et al 2017). Furthermore, quadriceps weakness may result in immediate changes in gait (Torry et al. 2000) but improving quadriceps strength does not either alter gait biomechanics in patients following ACLR (Lepley et al. 2015) or those with knee OA (Davis et al. 2019; DeVita et al. 2016). A stiff knee strategy characterized by more extended knee and smaller quadriceps related (internal knee extensor) moment during single-leg landing tasks during a battery of hop tests has been reported (Roewer et al. 2011; Lewek et al. 2002). When considering a suitable cut off value for quadriceps strength, Pietrosimone et al. (2016) recruited 96 subjects (62 females, and 34 males) following ACLR at six months. Pietrosimone et al. (2016) reported weaker quadriceps during isometric contractions (<3.1 $N.m.kg^{-1}$) displayed more extended knees throughout stance and smaller moments and greater vertical ground reaction force (vGRF) in the first 20% of stance than individual who met strength cut off values (>3.1 $N.m.kg\text{-}^{1}$). Gokeler et al. (2017) reported only 35.7% of patient's (22 males and 6 females) following ACLR at six months passed criterion for the peak torque at 60º/s normalized to BW (>3.1 $N.m.kg^{-1}$) for the involved knee. In the recent study by Herrington et al. (2018), isometric, concentric and eccentric contraction of quadriceps strength was assessed on 15 professional soccer players following ACLR at 7.8 months postoperatively, with over 80% of the players failing to exceed the LSI criteria of ≥90% for the strength test. However, Herrington et al. (2018) reported 75% of the cohort passed the ≥90% criteria for hop test. Studies by Herrington et al. (2018); Palmieir-Smith et al. (2009); Pietrosimone et al. (2016) and Gokeler et al. (2017) demonstrated a significant deficit in quadriceps strength and activation and to a lesser extent, performance during hop tests, despite the players being deemed fit to return to play at six months following ACLR.

When considering the cut off values, for isokinetic knee strength and SLHD, the relative levels of quadriceps strength (absolute strength normalized to body mass), as opposed to LSI, are rarely reported in the literature for an ACLR patient. The absolute strength is the force generated irrespective of body weight, whereas the relative strength is the force generated relative to body weight (Clark 2001). The most frequently reported variable is the LSI; therefore, making it difficult to understand the relative levels of quadriceps performance when the LSI uses rather than the relative level of quadriceps strength ($N.m.kg^{-1}$). Furthermore, the use of a contralateral limb as a reference limb comparison using metric such as LSI has been questioned (Herrington et al. 2018) because it may underestimate the actual level of the quadriceps deficit. Chung et al. (2015) stated that the contralateral limb of an ACLR patient at three and six months are often significantly weaker when compared with a control limb in non-injured individual or that limb pre-operatively.

Regardless of previously reported appropriate cut off values in isokinetic knee strength (>3.1 $N.m.kg^{-1}$) and SLHD (LSI≥ 90%), the deficits in kinetic (joint loading) and kinematic (joint motion) were detected in the patients following ACLR during SLHD (Kotsifaki et al. 2020). Symmetrical SLHD test does not indicate restoration of normal lower-limb kinematics or kinetics (Kotsifaki et al. 2020), ACLR patient tends to offload their reconstructed knee, landing with less knee external flexion moment and less knee energy absorption. The LSI< 90% during SLHD for the ACLR limb compared with the non-injured leg is usually associated with compensatory movements at the hip, ankle or knee joint (Kotsifaki et al. 2020). Therefore, focusing on cut off values for both tasks (SLHD and isokinetic knee strength) and using the non-injured limb as a reference limb following ACLR at three and six months is likely to be insufficient to assess knee function adequately. Furthermore, neglecting the quality of landing (2D FPPA) during SLS and SLHD to determine knee valgus angle along with QASLS to examine full-body movement, provide the bigger picture for sports physiotherapist to discover the risk of recurrent ACL injury.

As discussed in chapter 2, the clinical impact of TSK, suggesting that fear of movement and re-injury can promote inadequate quality rehabilitation and decreased physical activity (Flanigan et al. 2015). In the study by Norte et al. (2019), 77 subjects were recruited following ACLR at six months postoperatively with mixed autograft type. The primary outcome measures used by Norte et al. (2019) included TSK, a battery of hop tests, isokinetic knee strength and PROs (IKDC, KOOS). The finding of Norte et al. (2019) was that the greater kinesiophobia was associated with worse outcome after ACLR.

There are three aims for this study; 1. To compare the result of KOOS, TSK, YBT, isokinetic knee strength, 2D FPPA during SLS and SLHD and QASLS during two tasks (SLS and SLHD) between ACLR patients at three months to the dominant limb of the control group (injured to non-injured limb; injured to control limb and non-injured to control limb). It was hypothesised that the control limb would perform better than both injured and non-injured leg of the ACLR group at three months. 2. To compare the result between ACLR at six months to control limb (injured to non-injured leg; injured to control limb and non-injured to control limb). It was hypothesised that the control limb would perform better than both injured and non-injured limb of ACLR at six months. 3. To compare the result between the injured limb of ACLR at three months to the injured limb of ACLR at six months. It was hypothesised that the injured limb of the ACLR at six months would perform better than the injured limb of three months postoperative ACLR. This study is original because no previous work has used multiple tests (KOOS, TSK, YBT, isokinetic knee strength test, 2D FPPA along with QASLS during two tasks (SLS and SLHD) for side-to-side comparisons for the ACLR group and the control group. Also, to examine the asymmetry analyses between the ACLR group (three and six months) and the control group on an adult male from the Middle East region. The use of single outcome measurement tools following ACLR at three months fail to capture enough comprehensive data to make a truly informed decision before commencing outdoor rehabilitation and return to sport. This study's findings will be practically significant because they will highlight the use of SLHD for the ACLR group at three months without clinical complication after 24 hours monitoring (no pain, no swelling and no stiffness) (refer to chapter 2 for further details). Also, the use of the isokinetic knee strength test with full knee range of motion along with the mode of concentric and eccentric contractions for the ACLR at three and six months postoperatively.

Method

Participants

Twenty recreationally active participants, all male (age 25.50 ± 4.35 years, height 170.37 ± 39.89cm, mass 76.60 ± 8.51kg) (Table 1), all of whom were part of Alahli sports club squad, and part of Up and Running sports medicine clinic in the United Arab of Emirates, volunteered for the study. The same inclusion and exclusion criteria, approval and consent procedures were used as previously outlined in chapter 3.

Twenty-seven male control subjects (age 25.67±4.95 years, height 168.52±8.95 mass 59.22±8.70) (Table 1), all of whom were part of Alahli sports club squad, and part of Up and Running sports medicine clinic in the United Arab of Emirates, volunteered for the study. The same exclusion criteria, approval and consent procedures were used as previously outlined in chapter 3.

Procedures

The same procedures for patient report outcomes (KOOS, TSK), YBT, single leg squat, single leg hop for distance, isokinetic knee flexors and extensors, 2D frontal plane projection angle and the qualitative score sheet (QASLS) during SLS and SLH were used as previously outlined in chapter 3.

Table 1: Descriptive data of included subjects for control group and ACLR at three and six months postoperatively (Mean± Standard deviation).

	ACLR 3&6 months (n=20)	Control group (n=27)
Age (years)	25.5±4.35	25.6±4.95
Height (cm)	170.3±39.89	168.5±8.95
Mass (kg)	76.6±8.51	59.2±8.70
Sex(male/female)	20/0	27/0
Leg length (%)	93.5±4.7	87.81±5.31
Sports (number)		
Basketball	5	8
Handball	2	5
Volleyball	5	7
Football	8	7
Limb dominance (right/left)	15/5	7/20
Injured limb (right/left)	16/4	N/A
Autograft (BPTB/Hamstring)	7/13	N/A
Mean time from injury to ACLR surgery(days)	±32	

Statistical Analysis

A post hoc power analysis (*G* Power, Version 3.1.7) with mean differences between two dependent means and existence sample sizes for the ACLR groups and the control group were used to understand the level of statistical power of an observed effect based on the sample size (Buchner et al. 2019). Power calculation for each individual outcome variables found it in table 4 &7. In total, 20 subjects for ACLR group and 27 subjects for the control group were included. The mean LSI values for Y balance test, isokinetic knee strength test, SLS, and SLHD were measured for ACLR group and the control group. Statistical analysis was performed in SPSS for Mac OS (IBM, New York, NY, USA). The normality of all data was inspected using a Shapiro–Wilks test. Independent t-tests were used for normally distributed data to compare the ACLR groups and control group. Mann Whitney U tests were performed for a non-normally distributed data to compare ACLR group and control group in terms of distance (YBT, SLHD), strength, KOOS, TSK and 2D FPPA during tasks (SLHD and SLS). Alpha was set for 0.05. Paired t-tests were used to compare between injured limb versus non-injured limb, injured limb versus dominant limb of the control group and non-injured limb versus control limb mean values (Barber et al., 1990; Clark, 2001). Bonferroni-corrected was used to reduce the likelihood of type 2 error from multiple pairwise comparisons. For each individual test Bonferroni-correction was set at an alpha level of 0.002 (Alpha level (0.05) x three limbs (injured limb versus non-injured limb, injured limb versus control limb and non-injured limb versus control limb) x 10 quantitative tests) and an alpha level of 0.005 (Alpha level (0.05) x one limb (injured limb at three months versus injured limb at six months) x 10 quantitative tests) for each individual task (Portney & Watkins, 2009; Stovitz et al. 2017). Also, 95% confidence intervals (CI) with lower bound and upper bound were calculated for ACLR group and control group between injured limb, non-injured limb and control limb values (Dankel et al., 2017; Gardner & Altman, 1986; Stovitz et al., 2017). Cohen's d (ES) was calculated (mean 1- mean 2/SD pooled) between ACLR and control group limbs (Portney & Watkins, 2009). Effect sizes of 0.20, 0.50, and 0.80 were considered small, medium, and large, respectively (Portney & Watkins, 2009).

Result

No subjects for ACLR and control group experienced pain during testing, and there were no adverse events. All data were normally distributed for the ACLR group at three and six months postoperatively and the control group (P>0.05).

Comparing the ACLR group at three months to the control group

Good power was observed during the YBT (injured and non-injured versus control limb), SLHD, 2D FPSLS (injured and non-injured versus control limb), QASLS, QASLH, PTQC, PTHC and KOOS (ADL, Sport and QOL) (Table 4). Low power was observed during the YBT (injured versus non-injured limb), FPSLS (injured versus non-injured limb), FPSLH, QASLS (non-injured versus control limb), QASLH (non-injured versus control limb), PTQE, PTHE, KOOS (pain and symptoms) and TSK (Table 4).
There was no significant side to side difference (p>0.002) for the YBT, 2D FPPA for SLS and SLHD (injured to non-injured limb), QASLS for SLS and SLHD, normalised peak torque hamstring and quadriceps eccentric contraction, KOOS (symptoms and ADL) and TSK (Table 4).

There was a significant side to side difference (p<0.002) for the SLHD, 2D FPPA for SLS and SLHD (injured limb to control limb), normalised peak torque for concentric contraction of quadriceps and hamstring muscle and KOOS (pain, sport and QOL) (Table 4). The YBT, QASLS (SLS and SLHD), normalised peak torque eccentric contraction of hamstring, KOOS (pain, symptoms and ADL) and TSK tests injured, non-injured, and control limb mean values and 95% CI were small with small ES

(Table 2- 4). The 2D FPPA during SLS and SLHD, normalised peak torque concentric contraction for quadriceps muscle and KOOS/sport tests injured limb, non-injured limb and control group mean values and 95% CI were quite different with medium ES (Table 2-4). The SLHD, normalised peak torque concentric contraction for hamstring and eccentric contraction for quadriceps muscles and KOOS/QOL tests between the ACLR group at three months and control group, mean values and 95% CI were quite different with large ES (Table 2-4). The LSI values were above 70% for the YBT (injured to non-injured limb), SLHD (injured to non-injured limb) and normalised peak torque quadriceps concentric (injured to non-injured limb) between the ACLR group at three months to the control group (Table 5). Also, the KOOS (pain, sport and QOL) were above 70% cut off values between the ACLR group at three months to the control group (Table 6).

Comparing the ACLR group at six months to the control group

Good power was observed during 2D FPSLH (injured versus control limb), QASLS, QASLH (injured and no-injured versus control limb), PTQE (injured and non-injured versus control limb), KOOS (Sport and QOL) and TSK (Table 4). Low power was observed during the YBT, SLHD, 2D FPSLS, 2D FPSLH (injured and non-injured versus control limb), QASLH (injured versus non-injured limb), PTQC, PTQE (injured versus non-injured limb), PTHC, PTHE, KOOS (pain, symptoms and ADL) (Table 4).

There was no significant side to side difference ($p>0.002$) for the YBT, SLHD, 2D FPPA for SLS and SLHD, QASLS for SLS (injured to control limb), QASLS for SLHD (injured to non-injured limb), normalised peak torque hamstring contraction, normalised peak torque quadriceps concentric contraction (injured to control limb and non-injured to control limb) and eccentric contraction of hamstring (injured to control limb and non-injured to control limb) and KOOS (pain, symptoms and ADL) ($p>0.05$) (Table 2- 4).

There was a significant side to side different ($p<0.002$) for the QASLS during SLS (injured to non-injured limb) and SLHD (injured to control limb), normalised peak torque for concentric contraction of quadriceps (injured to non-injured limb) and eccentric contraction for hamstring (injured to non-injured limb) and quadriceps muscles, KOOS (sport and QOL) (Table 2- 4). The YBT, SLHD, 2D FPPA during SLS and SLHD, normalised peak torque concentric contraction of hamstring, KOOS (ADL and QOL) and TSK tests injured, non-injured, and control limb mean values and 95% CI were small with small ES (Table 2-4). The QASLS during SLS and SLHD, normalised peak torque hamstring eccentric and KOOS (pain, symptoms and sport) tests injured limb, non-injured limb and control group mean values and 95% CI were quite different with medium ES (Table 2-4). The normalised peak torque concentric and eccentric contractions for quadriceps muscle tests between the ACLR group at six months and control group, mean values and 95% CI were quite different with large ES (Table 2- 4). The LSI values for QASLS during SLS (non-injured to control limb), QASLS during SLHD (injured and non-injured to control limb) and normalised peak torque quadriceps eccentric (injured to non-injured limb) were below 90% cut off values between the ACLR group at six months to the control group (Table 5).

Comparing the ACLR injured limb group at three and six months

Good power was observed during the SLHD, 2D FPSLS, 2D FPSLH, QASLH, PTQC, PTQE, PTHC, KOOS (Symptoms, ADL and Sport) and TSK (Table 7). Low power was observed during the YBT, QASLS, PTHE, KOOS (pain and QOL) (Table 7).

There was no significant side to side difference ($p>0.005$) for the YBT, SLHD, QASLS for SLHD, normalised peak torque hamstring eccentric, normalised peak torque quadriceps concentric, KOOS (pain, QOL and ADL) and TSK (Table 7).

There was a significant difference ($p<0.005$) for 2D FPPA during SLS and SLHD, QASLS during SLS, normalised peak torque for hamstring concentric and quadriceps eccentric and KOOS (symptoms and sport) (Table 7). The YBT, SLHD, 2D FPPA during SLS, QASLS during SLS, normalised peak torque concentric and eccentric contractions for both hamstring and quadriceps muscle group, KOOS (pain, symptoms and QOL) and TSK tests injured to-injured limb mean values and 95% CI were small with small ES (Table 2-3 & 7). The 2D FPPA during SLHD, QASLS during SLHD and KOOS (ADL and sport) tests injured limb to injured limb mean values between ACLR group at three and six months and 95% CI were quite different with medium ES (Table 2-3 & 7). The LSI values for normalised peak torque eccentric contraction for quadriceps muscle (injured to injured limb) were below 90% cut off values between the ACLR injured limb group at three and six months (Table 5).

Table 2: Mean, standard deviation (SD) and 95% confidence interval (CI) between ACLR subjects at three and six months (injured limb to non-injured) and dominant side of control group for YBT, SLHD, 2D FPPAº (SLS and SLHD), QASLS (SLS and SLHD) tasks and normalised peak torque ($N.m.kg^{-1}$) for quadriceps and hamstring muscles. The distance hopped was normalized to a percentage of leg length (distance from anterior superior iliac spine to medial malleolus) and multiplying by 100.

	Mean					SD					95% CI				
	IN3	NI3	IN6	NI6	CTRL	IN3	NI3	IN6	NI6	CTRL	IN3	NI3	IN6	NI6	CTRL
YBT (%)	60.69	62.08	64.84	64.89	67.49	5.62	5.15	7.14	7.52	6.05	58.0-63.3	59.6-64.4	61.5-68.1	61.3-68.4	65.1-69.8
SLHD (%)	150.68	168.7	128.97	132.02	118.01	21.7	19.29	29.33	24.72	26.61	140.4-160.8	159.6-177.7	115.2-142.7	120.4-143.5	118.1-121.9
FPSLS°	23	21	20	18	17	4	5	3	3	3	21-25	19-23	18-21	17-20	16-19
FPSLHD°	25	22	21	18	17	6	7	5	5	3	22-28	18-25	19-23	16-21	16-18
QLSLS	5	4	5	3	4	1	1	1	1	1	4.1-5.1	3.4-4.6	3.4-4.3	2.5-3.2	3.3-4.7
QLSLHD	5	4	3	3	4	1	1	1	1	1	4.1-4.9	3.6-4.4	2.7-3.2	2.8-3.4	4.4-5.1
PTQC ($N.m.kg^{-1}$)	2.22	2.57	1.85	2.00	1.57	.45	.39	.60	.60	0.43	2.0-2.4	2.3-2.7	1.5-2.1	1.7-2.2	1.3-1.7
PTQE ($N.m.kg^{-1}$)	1.50	1.57	1.95	2.17	1.51	.24	.24	.49	.47	.53	1.3-1.6	1.4-1.6	1.7-2.2	1.3-1.7	1.2-1.7
PTHC ($N.m.kg^{-1}$)	2.55	2.76	1.92	1.92	1.64	.45	.33	.42	.44	0.29	2.3-2.7	2.6-2.9	1.9-2.3	1.2-1.7	1.5-1.7
PTHE ($N.m.kg^{-1}$)	1.71	1.75	1.92	2.04	1.77	.30	.24	.42	.43	0.43	1.5-1.8	1.6-1.8	1.7-2.1	1.8-2.2	1.5-1.9

Percentage of leg length (LL%)= (distance hopped (cm) ÷ leg-length (cm) x 100.; 2D frontal plane projection angle for single leg squat (FPSLSº) and single leg hop for distance (FPSLHDº), Qualitative analysis loading for single leg squat (QSLS) and single leg hop for distance (QSLHD);Injured limb (IN); Non-injured limb (NI); control limb (CTRL) and Standard deviation (SD), normalised peak torque quadriceps concentric contraction (PTQC); Normalised peak torque quadriceps eccentric contraction (PTQE); Normalised peak torque hamstring concentric contraction (PTHC); Normalised peak torque hamstring eccentric contraction (PTHC).

Table 3. Mean, Standard deviation (SD) and 95% confidence interval (CI) between ACLR group (three and six months) control group for KOOS and TSK.

	Mean			SD			95% CI		
	ACLR3	ACLR6	CTRL	ACLR3	ACLR6	CTRL	ACLR3	ACLR6	CTRL
KOOS-Pain	83.20	89.00	92.59	19.2	9.65	10.20	80.4-85.9	84.4-93.5	88.5-96.6
KOOS-Symptoms	61.00	70.45	65.85	7.09	11.33	6.96	57.6-64.3	65.1-75.7	63.0-68.6
KOOS-ADL	85.30	92.65	94.37	5.73	6.63	8.17	82.6-87.9	89.5-95.7	91.1-97.6
KOOS-Sport	48.05	65.50	88.70	16.83	21.02	14.58	40.1-55.9	55.6-75.3	82.9-94.4
KOOS-QOL	49.95	63.90	86.48	8.11	24.61	12.67	46.1-53.7	52.3-75.4	81.4-91.4
TSK	34.35	31.30	35.19	3.71	3.71	4.52	32.6-36.0	28.9-33.6	33.3-36.9

KOOS-Pain= knee osteoarthritis outcome score for the pain subscale; KOOS-symptoms= knee osteoarthritis outcome score for the symptom’s subscale; KOOS-ADL= knee osteoarthritis outcome score for the activity daily living; KOOS-sport= knee osteoarthritis outcome score for sport; KOOS-QOL= knee osteoarthritis outcome score for the quality of life; TSK=Tampa scale kinesiophobia

Table 4: Mean pairwise comparison between ACLR group (three and six months) and control group

Variables	P values for three months	P values for six months	ES for three months	ES for six months	Power (1-β err prob) for three months	Power (1-β err prob) for six months
ANTRIN versus ANTRNI	.73	1.00	.40	.09	.29	.05
ANTRIN versus ANTRCTRL	.006	.52	.40	.09	.97	.26
ANTRNI versus ANTRCTRL	.018	.74	.40	.09	.89	.24
SLHIN versus SLHNI	.001	1.00	.87	.44	.95	.07
SLHIN versus SLHCTRL	.001	.04	.87	.44	.99	.25
SLHNI versus SLHCTRL	.001	.005	.87	.44	.99	.44
FPSLSIN versus FPSLSNI	.35	.17	.67	.41	.41	.53
FPSLSIN versus FPSLSCTRL	.001	.006	.67	.41	.99	.72
FPSLSNI versus FPSLSCTRL	.014	.23	.67	.41	.82	.20
FPSLHIN versus FPSLHNI	.26	.29	.70	.38	.63	.54
FPSLHIN versus FPSLHCTRL	.001	.008	.70	.38	.99	.88
FPSLHNI versus FPSLHCTRL	.04	.59	.70	.38	.78	.18
QASLSIN versus QASLSNI	.18	.001	.34	.70	.98	1.00
QASLSIN versus QASLSCTRL	.017	1.00	.34	.70	.91	.91
QASLSNI versus QASLSCTRL	.99	.005	.34	.70	.05	.91
QASLHIN versus QASLHNI	.42	.95	.32	.52	.98	.05
QASLHIN versus QASLHCTRL	.42	.001	.32	.52	.91	.91
QASLHNI versus QASLHCTRL	1.00	.012	.32	.52	.05	.91
PTQCIN versus PTQCNI	.001	.001	.78	.90	.93	.18
PTQCIN versus PTQCTRL	.001	.50	.78	.90	.99	.42
PTQCNI versus PTQCTRL	.001	.11	.78	.90	1.00	.78
PTQEIN versus PTQENI	.48	.001	.89	.81	.23	.49
PTQEIN versus PTQECTRL	1.00	.002	.89	.81	.05	.81
PTQENI versus PTQECTRL	1.00	.001	.89	.81	.07	.99
PTHCIN versus PTHCNI	.018	1.00	.85	.28	.59	.05
PTHCIN versus PTHCTRL	.001	.04	.85	.28	1.00	.73
PTHCNI versus PTHCTRL	.001	.05	.85	.28	1.00	.70
PTHEIN versus PTHENI	1.00	.001	.03	.64	.09	.22
PTHEIN versus PTHECTRL	1.00	.42	.03	.64	.08	.21
PTHENI versus PTHECTRL	1.00	.06	.03	.64	.05	.54
KOOSP versus KOOSCTRL	.001	.23	.45	.73	.52	.33
KOOS/Symptoms versus KOOSCTRL	.008	.28	.31	.61	.62	.50
KOOS/ADL versus KOOSCTRL	.002	.91	.39	.01	.98	.16
KOOS/Sport versus KOOSCTRL	.001	.001	.78	.51	1.00	.99
KOOS/QOL versus KOOSCTRL	.001	.001	.85	.46	1.00	.99
TSK versus TSKCTRL	.41	.006	.03	.03	.10	.95

ANTRIN=anterior reach balance test injured limb(ANTRIN); ANTRNI= anterior reach balance test non-injured limb; ANTRCTRL= anterior reach balance test control group; ES= effect size; SLHIN=single leg hop distance injured limb; SLHNI= single leg hop distance non-injured limb; SLHCTRL= single leg hop distance control group; FPSLSIN°= 2D frontal plane projection angle for single leg squat injured limb; FPSLSNI°= 2D frontal plane projection angle for single leg squat non-injured limb; FPSLHIN°= 2D frontal plane projection angle for single leg hop injured limb; FPSLHNI°= 2D frontal plane projection angle for single leg hop non-injured limb; FPSLSCTRL°= 2D frontal plane projection angle for single leg hop control group; FPSLSCTRL°= 2D frontal plane projection angle for single leg squat control group; QASLSIN= Qualitative analysis single leg squat injured limb ; QASLSNI= Qualitative analysis single leg squat non-injured limb; QASLSCTRL= Qualitative analysis single leg squat control group; QASLHIN= Qualitative analysis single leg hop injured limb; QASLHNI= Qualitative analysis single leg hop non-injured limb; QASLHCTRL= Qualitative analysis single leg hop control group; PTQCI=Normalised peak torque quadriceps concentric contraction injured limb; PTQCNI=Normalised peak torque quadriceps concentric contraction non-injured limb; PTQCTRL=Normalised peak torque quadriceps concentric contraction control group; PTQEI= Normalised peak torque quadriceps eccentric contraction injured limb; PTQENI= Normalised peak torque quadriceps eccentric contraction non-injured limb; PTQECTRL= Normalised peak torque quadriceps eccentric contraction control group; PTHCI= Normalised peak torque hamstring concentric contraction injured limb; PTHCNI= Normalised peak torque hamstring concentric contraction non-injured limb; PTHCTRL= Normalised peak torque hamstring concentric contraction control group; PTHEI= Normalised peak torque hamstring eccentric contraction injured limb; PTHENI= Normalised peak torque hamstring eccentric contraction non-injured limb; PTHECTRL= Normalised peak torque hamstring eccentric contraction control group; KOOSCTRL= KOOS control group and TSKCTRL= TSK control group

Table 5. The mean pairwise LSI comparison between the ACLR group (three and six months) and control group.

Variables	ACLR3IN versus ACLR3NI	ACLR3IN versus CTRL	ACLR3NI versus CTRL	ACLR6IN versus ACLRNI	ACLR6IN versus CTRL	ACLR6NI versus CTRL	ACLR3IN versus ACLR6IN
YBT	97.7	89.92	91.98	99.9	97.07	96.14	93.59
SLHD	89.31	127.68	142.95	97.68	107.28	111.87	116.83
FPSLS	109.15	132.06	120.99	107.45	113.46	105.59	116.39
FPSLHD	116.13	145.23	125	112.17	119.76	106.78	121.26
QASLS	125	125	100	166.6	125	75	100
QASLHD	125	125	100	100	75	75	166
PTQC	86.38	141.4	163.69	92.5	117.83	127.38	120
PTQE	95.54	100	96.17	89.6	129.13	143.7	76.9
PTHC	92.39	155	168.29	100	117.07	117.11	132.8
PTHE	97.71	96.61	98.87	94.11	108.47	115.25	112.28

YBT= Y balance test; SLHD=single leg hop for distance; FPSLS= frontal plane projection angle during single leg squat; FPSLHD= frontal plane projection angle during SLHD; QASLS= Qualitative analysis during single leg squat; QASLHD= Qualitative analysis during SLHD, PTQC= peak torque for quadriceps concentric contraction; PTQE= peak torque for quadriceps eccentric contraction PTHC= peak torque for hamstring concentric contraction PTHE= peak torque for hamstring eccentric contraction.

Table 6. The mean LSI of the KOOS and TSK subjective questionnaires between the ACLR group (three and six months) and control group.

Variables	ACLR3 versus CTRL	ACLR6 versus CTRL	ACLR3 versus ACLR6
KOOSP	89.85	96.12	93.4
KOOS/symptoms	92.63	106.9	86.5
KOOS/ADL	90.38	98.17	92.06
KOOS/Sport	54.17	73.84	73.35
KOOS/QOL	57.75	74.88	78.16
TSK	97.16	88.94	109.7

KOOS-Pain= knee osteoarthritis outcome score for the pain subscale; KOOS-symptoms= knee osteoarthritis outcome score for the symptom's subscale; KOOS-ADL= knee osteoarthritis outcome score for the activity daily living; KOOS-sport= knee osteoarthritis outcome score for sport; KOOS-QOL= knee osteoarthritis outcome score for the quality of life; TSK=Tampa scale kinesiophobia

Table 7. Mean pairwise comparison between ACLR group (injured limb at three months to injured limb at six months).

Variables	P values	ES	Power (1-β err prob)
ANTRIN3 versus ANTRIN6	.026	.23	.77
SLHIN3 versus SLHIN6	.27	.23	.93
FPSLSIN3 versus FPSLSIN6	.001	.49	.95
FPSLHIN3 versus FPSLHIN6	.001	.64	.94
QASLSIN3 versus QASLSIN6	.005	.34	.05
QASLHIN3 versus QASLHIN6	.001	.78	1.00
PTQCIN3 versus PTQCIN6	.066	.16	.82
PTQEIN3 versus PTQEIN6	.001	.46	.99
PTHCIN3 versus PTHCIN6	.001	.49	.99
PTHEIN3 versus PTHEIN6	.068	.16	.66
KOOSP3 versus KOOSP6	.016	.26	.31
KOOS/Sym3 versus KOOS/Sym6	.004	.35	.98
KOOS/ADL3 versus KOOS/ADL6	.001	.52	.99
KOOS/Sport 3versus KOOS/Sport6	.001	.51	.96
KOOS/QOL3 versus KOOS/QOL6	.015	.27	.77
TSK3 versus TSK6	.047	.19	.93

ANTRIN3=anterior reach balance test injured limb three months post ACLR; ANTRIN6= anterior reach balance test injured limb six months post ACLR; ES= effect size; SLHIN3=single leg hop distance injured limb three months post ACLR; SLHIN6= single leg hop distance injured limb six months post ACLR; FPSLSIN3°= 2D frontal plane projection angle for single leg squat injured limb three months post ACLR; FPSLSIN6°= 2D frontal plane projection angle for single leg squat injured limb six months post ACLR; FPSLHIN3°= 2D frontal plane projection angle for single leg hop injured limb three months post ACLR; FPSLHIN6°= 2D frontal plane projection angle for single leg hop injured limb six months post ACLR; QASLSIN3= Qualitative analysis single leg squat injured limb three months post ACLR; QASLSIN6= Qualitative analysis single leg squat injured limb six months post ACLR; QASLHIN3= Qualitative analysis single leg hop injured limb three months post ACLR; QASLHIN6= Qualitative analysis single leg hop injured limb six months post ACLR; PTQCIN3=Normalised peak torque quadriceps concentric contraction injured limb three months post ACLR; PTQCIN6=Normalised peak torque quadriceps concentric contraction injured limb six months post ACLR; PTQEIN3= Normalised peak torque quadriceps eccentric contraction injured limb three months post ACLR; PTQEIN6= Normalised peak torque quadriceps eccentric contraction injured limb six months post ACLR; PTHCIN3= Normalised peak torque hamstring concentric contraction injured limb three months post ACLR; PTHCIN6= Normalised peak torque hamstring concentric contraction injured limb six months post ACLR; PTHEIN3= Normalised peak torque hamstring eccentric contraction injured limb three months post ACLR; PTHEIN6= Normalised peak torque hamstring eccentric contraction injured limb six months post ACLR; KOOSP3= pain three months post ACLR; KOOSP6= pain six months post ACLR; KOOS/Sym3=symptoms three months post ACLR and KOOS/Sym6= symptoms six months post ACLR.

Discussion

The first aim of this study was to assess KOOS, TSK, isokinetic knee flexor and extensor strength, YBT, and 2D FPPA and QASLS during SLS and SLHD tests between the ACLR patients at three months post operation and the control group so comparing injured to non-injured limb, injured to control limb and non-injured to control limb. It was hypothesised that the control limb would perform better than both limbs of the ACLR at three months and the non-injured limb would perform better than the injured limb. The findings of the current study demonstrate that the control limb showed better scores in the YBT, 2D FPPA and QASLS during SLS and SLHD, normalised peak torque eccentric contraction of hamstring and all subscales of KOOS than both limbs of the ACLR at three months (Table 2-4). However, the control limb demonstrated poorer results in SLHD, normalised peak torque concentric contraction for hamstring and quadriceps muscle, normalised peak torque eccentric contraction for quadriceps muscle and TSK compared to the injured and non-injured limb of the ACLR at three months post-op (Table 2-4).

The second aim of this study was to examine the KOOS, TSK, isokinetic knee flexor and extensor, YBT, and 2D FPPA during SLS and SLHD tests between the ACLR patients at six months post-operation and the control group comparing injured to non-injured limb, injured to control limb and non-injured to control limb. It was hypothesised that the control limb would perform better than both limbs of the ACLR at six months and the non-injured limb would perform better than the injured limb. The findings of the current study demonstrate that the control limb had better scores in YBT, 2D FPPA during SLS and SLHD and all subscales of KOOS than both limbs of the ACLR group at six months (Table 2-4). However, the control limb demonstrated poorer results in the SLHD, QASLS (SLS and SLHD), normalised peak torque concentric and eccentric contractions for hamstring and quadriceps muscles, KOOS/symptoms and TSK compared to the injured and non-injured limb of the ACLR at six months post-op (Table 2-4).

The third aim of this study was to examine the KOOS, TSK, isokinetic knee flexor and extensor, YBT, and 2D FPPA during SLS and SLHD tests between injured limbs for the ACLR group at three and six months. It was hypothesised that the ACLR injured limb at six months would perform better scores than the ACLR injured limb at three months post-op. The findings of the current study demonstrate that the ACLR injured limb at six months had better scores in the YBT, 2D FPPA and QASLS (SLS and

SLHD), normalised peak torque quadriceps eccentric, KOOS and TSK than the ACLR injured limb at three months (Table 2-4). However, the ACLR injured limb at three months demonstrated better scores in the SLHD and normalised peak torque quadriceps and hamstring concentric and eccentric contraction of the hamstring muscle (Table 2-4).

Comparison of the present data (Table 2-7) to previous literature is not possible because no other work has reported such data (KOOS, TSK, YBT, isokinetic knee strength test, 2D FPPA for two tasks (SLS and SLHD) and QASLS during (SLS and SLHD) for an adult male from United Arab of Emirates with ACLR at three and six months postoperatively. The alternative is to compare the present data (Table 2-7) to values reported for other adult male athletes and recreational athletes and mixed sex adult groups, which will be attempted were possible.

Comparing the ACLR group at three months to the control group

Garrison et al. (2015) recruited forty participants (20 males, 20 females) with a mean age of 17.2±3.8 years. at 12 weeks post ACLR, they found that Y balance anterior reach deficits were present in the involved and uninvolved side of ACLR patients compared to the control group. However, in the current study, there was no significant different (p>0.002) (note Bonferroni-corrected alpha level was calculated as 0.002) between the injured and non-injured limb, non-injured to control limb and injured to control limb for the ACLR and control group with small ES (0.40) (Table 4). But the good power was observed during the YBT between injured and non-injured versus control limb, suggesting that there are differences exist for YBT (Table 4). However, similar 95% CI (Table 2) were reported for YBT, suggesting there is no real differences exist in YBT performance test. Observed power is an estimate of the power based on the observed effect size in a study. However, because the other parameters such as sample size and significance criterion that are needed to compute power, the observed effect size is the only parameter that needs to be observed to estimate power. But, observed power is still an estimate based on an observed effect size because power depends on the effect size in the population and observed effect size in a sample is just an estimate of the population effect size (Yuan and Maxwell 2005). Therefore, the use of ES alongside P- values are advocated because P-values alone do not indicate the magnitude of difference between two central tendencies for the same variable (Stovitz et al., 2017). Use of the 95% CI is advocated because effect size distorts study findings and be misleading (Dankel et al. 2017).

The LSI values for YBT (89.9%) in the current study were close to cut off value for the injured and non-injured limb of ACLR at three months before return to running (Table 5). But the LSI values for YBT in the injured to control limb and non-injured to control limb were above cut off values (Table 5). Therefore, the sample of our study has shown no deficit in YBT balance test between limbs of the ACLR group at three months to control group. The YBT aims to assess aspects of dynamic movement control and providing information that is relevant for return to running and complements the KOOS, TSK, 2D FPPA and QASLS during SLS and SLHD, and isokinetic knee strength tests. Rambaud et al. (2017); Adams et al. (2012); Joreitz et al. (2016) reported the criterion before jogging after 12 weeks of ACLR includes full knee ROM> 95% of the non-injured knee, symmetrical gait pattern, isokinetic knee strength (LSI>70%), SLS>45° knee flexion, hop test LSI>70% and YBT LSI≥90. Therefore, in the current study, the YBT≥90 met the cut off values following ACLR at three months. The finding of the YBT in the present study on the ACLR at three months suggest that despite the recommendation by Rambaud et al. (2017); Adams et al. (2012); Joreitz et al. (2016) that the LSI≥90 indicate readiness for return to running, it was unlikely the patient was ready because of deficits in other measures, hence the value of multiple measures.

The utilisation of SLHD testing and prior to running was advocated by Adams et al., (2012); van Grinsven et al., (2010); Rambaud et al., (2017); Kvist, (2004); Wilk et al., (2012) at three months following ACLR, when the patients met the criterion return to run (Adams et al., 2012; Rambaud et al., 2017).

The current study is the first study to examine the distance of SLHD and simultaneously the quality of landing (2D FPPA and QASLS) following ACLR at three months. The SLHD assesses the force production during take-off, knee valgus angle and quality of full-body movement during landing between the injured limb and non-injured limb of the ACLR group (refer to chapter 2 for further details) were the knee is responsible for a high proportion of the force absorption. Also, performing the SLHD at three months is safe because, after ACLR, all the participants during rehabilitation perform SLS before progressing to the SLHD. The SLS assesses neuromuscular control from trunk to the ankle joint with lower vertical ground reaction forces (i.e., no ground impact) meaning there is no excessive load applied to the graft of ACLR. In the current study, once the ACLR group performed the SLS with good quality of movement (monitored by 2D FPPA and QASLS) during the rehabilitation process, the ACLR group progressed to more demanding tasks SLHD. As mentioned in chapter 2, Alahli club's physiotherapist demonstrated how to perform good quality of the SLHD with proper knee flexion angle (knee flexion angle >45˚) and maintain knee alignment with the second toe during landing to place less load on the graft of ACLR subjects. As mentioned in the results section, there was no pain, swelling and stiffness reported. Therefore, the SLHD is safe from the loading point of view when the observation and feedback are given to the ACLR group and progress from SLS to the SLHD and then jogging.

The LSI values for SLHD, 2D FPPA and QASLS during SLS and SLHD (ranged from 89.31%-145.23%) (Table 5) were above 70% cut off value for commencing SLHD and jogging in a straight-line (Adams et al., 2012; Rambaud et al., 2017). However, there was a significant difference ($p<0.002$) between limbs of ACLR at three months and the control limb for SLHD with good power >0.80, large ES (0.87) (Table 4). The quality of landing (2D FPPA and QASLS) for the control limb during SLS and SLHD was better than the ACLR group at three months, suggesting that the control group had better full-body control during unilateral landing tasks (Table 2). Considering the quality of the landing (2D FPPA and QASLS) during SLS and SLHD, there were no significant differences ($p>0.002$) (Table 4) between the injured and non-injured limb of ACLR at three months. However, the good power >0.80 was observed during 2D FPPA during SLS (injured and non-injured versus limb control), 2D FPPA during SLHD (injured versus control limb) and QASLS during SLS and SLHD (Table 4), suggesting that there were significant results existing between the ACLR limbs group at three months to control limb. This suggests that both limbs of the ACLR at three months require more neuromuscular control rehabilitation exercise before introducing high load (change of direction and plyometrics drills) to the knee joint (Herrington et al 2013).

Studies by Adams et al. (2012) and Rambaud et al. (2017) reported that strength was the most frequently reported category of a return to running criteria (n=31, 16%). The hamstring and quadriceps muscles have an essential role in the active stabilisation of the knee and neuromuscular control (Tourville et al. 2014; Decker et al. 2011). The mode of muscle contractions is also crucial during running, change of direction and plyometric. Further, an athlete will require sufficient eccentric strength to reduce momentum during the braking phase, isometric strength during the plant (amortisation) phase and concentric strength during the propulsion phase to help re-accelerate in the opposite direction (Spiteri et al. 2014; Jones et al. 2017). Jones et al. (2017) stated that athletes with greater eccentric strength could approach faster as they are better able to tolerate the greater ground reaction forces (GRFs) associated with a faster approach prior to stopping or changing direction. Therefore, adequate strength of both hamstring and quadriceps are necessary before return to running, Adams et al. (2012) and Rambaud et al. (2017) reported the LSI>70% cutoff values before return to running. Considering the cutoff values for normalised peak torque of hamstring and quadriceps muscles following ACLR at three months, there is no study that has been reported data for the ACLR group at three months postoperatively. Therefore, in the current study, the control limb would be the reference limb. The LSI values for the current study for the ACLR group at three months to control group were above 70% between the injured, non-injured and control limb (Table 5). Regarding normalised peak torque mean values for both hamstring and quadriceps muscles, the injured and non-injured limbs for ACLR group at three months showed a better result than the control group, suggesting that both limbs of ACLR group at three months were stronger than reference limb (control limb) (Table 2). However, there was a significant side to side difference ($p<0.002$), good power >0.80 between the ACLR group at three months and control limb with the medium to large ES (.78-.89), and 95% CI were quite different (Table 2,4). Further, there was no significant different ($p>0.002$) between the ACLR group at three months, and the control limb with normalised peak torque eccentric contraction for hamstring (Table 4). The low power was observed during normalised peak torque quadriceps and hamstring eccentric contractions (Table 4) between the ACLR group at three months and control limb, with small ES (.03) and 95% CI were no different (Table 2,4), suggesting that there is no real differences existing between the ACLR group at three months and the control group. But concerning the cutoff values, both cutoff values (LSI>70% and normalised peak torque>reference limb) were higher than the recommended criterion before return to running. Therefore, all the patients in the current study were safe to commence jogging and hopping at three months postoperatively to prepare them for the next phase of more demand rehabilitation, if strength LSI is used as the primary criteria. Though the levels of strength fall below cut off value recommended by Pietrosimone et al (2016) for return to sport so caution would need to be applied when undertaking non-linear activities at this stage.

Comparing the ACLR group at six months to the control group

Clagg et al. (2015) recruited **s**ixty-six participants (mean age= 17.6 years) following ACLR at six months postoperatively and forty-seven control participants (mean age=17.0 years). Clagg et al. (2015)

reported the ACLR group showed worse anterior reach performance on both limbs compared to the control group with no difference between two groups in both posterior-medial and posterior-lateral reach directions at the time of return to play (6 months post-ACLR). However, in the current study, there was no significant side to side differences (p>0.002) between the limbs of the ACLR at six months and the control group with underpower <0.80, and small ES (0.09) (Table 4). Further, 95% CI were reported similar, suggesting there is no real differences exist for YBT performance between limbs of ACLR at six months and the control group (Table 2). The LSI values for YBT (ranged from 96.14%-99.9%) in the current study which were above the established cutoff value for the ACLR at six months, and the control group (Table 5).

When considering acceptable LSI values for hop test performance to return safely to more intense sports specific activity following ACLR, these have been reported as greater than 90% (Myer et al., 2011 and Thomee et al. 2011). Xergia et al. (2013) reported 5% of patients had greater than 90% LSI in SLHD and Gokeler et al. (2017) reported only 78.5% of patients passed LSI>90% for SLHD following ACLR at six months. In the current study, 90% of the ACLR group at six months passed the LSI cutoff values during SLHD (Table 5). However, there were no significant differences (p>0.002) between the injured limb to control limb and non-injured limb to control limb during SLHD though this was underpowered <0.80 and had small ES (0.44) and 95% CI were quite different, suggesting that the control group showed poorer result compared to the ACLR group at six months (Table 2,4). The ACLR group at six months passed the established LSI cut-off values when calculated comparing the injured and non-injured limbs normalised reach distance during single leg hop and when calculated using the control limb (Table 5). This would appear at least appear to be in part to the better performance of SLHD in ACLR group (three and six months) which might be related to the regular exercise rehabilitation sessions (performing two sessions a day and 12 sessions per week) compared to an absence of strength training in the control group in the current study. It could be reasonable to assume the poorer performance for the control group in the SLHD compared to the ACLR group might be related to their lower levels of strength hence their force development abilities.

The quality of landing (2D FPPA) during SLS and SLHD was no different (p>0.002) between the injured limb of the ACLR at six months and the control for 2D FPPA during SLS and SLHD. The low power was observed during 2D FPPA during SLS and SLHD (Table 4) between the injured and non-injured limb of the ACLR group at six months to the control limb, suggesting that there is insufficient power to be fully confident in the significance of the difference in the results between two groups.

Similarly, the small ES (Table 4) suggests that the injured limb of ACLR at six months may have shown poor quality of landing (more knee valgus) compared to non-injured and the control limb, but some of these differences may have been due to chance.

Considering QASLS during SLS and SLHD, they were significantly different ($p<0.002$) between limbs of the ACLR at six months to control group, good power >0.80 with medium ES suggesting there are real differences exist during SLS and SLHD performance between both groups. Furthermore, despite good outcome for LSI reported for ACLR at six months and compared to the control group based on distance, the quality of landing during SLHD following ACLR at six months showed poor kinematic (knee valgus at six months= 21º versus control group=17º) (Table 2). Therefore, even achieving LSI >90 hop distance for ACLR group at six months compared with non-injured leg may still be associated with other issues such as compensatory movements at the hip, ankle or knee joint which could make the patient vulnerable to injury, hence combining quality of landing with hop distance provides a more complete and useful outcome measure.

The LSI values for the normalised peak torque eccentric contraction for quadriceps (89.6%) and hamstring (94.11%) and concentric contraction for quadriceps (92.5%) were below the typical score of (LSI=100) (Thomee et al. 2011) for those patients would attempt to participate to level one sports (jumping, pivoting, and change of direction), so these patients appear to have a significant deficit when considering return to sport.

An acceptable cutoff value for absolute peak torque value (>3.1 $N.m.kg^{-1}$) was reported by Pietrosiomone et al. (2016) during isokinetic isometric knee strength testing following ACLR at six months. In the present study, deficit during eccentric and concentric quadriceps reported at three, and six months following ACLR with 21% at three months and 26% at six months passed the relative peak torque value >3.1$N.m.kg^{-1}$. The eccentric muscle strength in the same velocity should score higher than concentric contraction (refer to chapter 2). Still, the mean relative values for eccentric quadriceps and hamstring contractions following ACLR at three months were less than mean values of concentric contractions for both muscle groups in the current study. It might due to fear and difficulty to perform eccentric and concentric quadriceps contractions during isokinetic testing following ACLR at three months. In the control group, only 4% passed this relative peak torque value. The poor strength of the control group in the present study might be due to the complexity of delivering muscular contraction during isokinetic knee strength testing. The control group therefore might require more isokinetic training sessions to gain familiarisation. Further, the control group's body mass was lower than the ACLR group in the current study, which might impact on knee extensor and flexor strength during isokinetic knee test. Kellis et al. (2000) and Harbo et al. (2012) stated that age, height, gender and body mass are related to muscle strength (peak torque) during isokinetic knee strength test. Harbo et al. (2012) stated the variables age, height and body mass accounted for 25% of the variation in strength. Kellis et al. (2000) found a significant relationship of concentric and eccentric isokinetic knee strength for both knee extensors and flexors of 73-93% relating to the combination of age, body mass, percentage of body fat and hours of training per week in 113 male subjects. These findings suggest that the clinicians should consider the age, height, body mass and learning effect when assessing the isokinetic knee strength test when recruiting the control group to the ACLR group for future study.

Pietrosimone et al. (2016) reported 31.25% of the subjects had > 3.1N.m.kg^{-1} and 68.75% <3.1 N.m.kg^{-1} so failed to meet the criteria following ACLR at six months with mixed sexes, which similar to the findings of this study. When assessing the LSI cutoff values, Pietrosimone et al. (2016) reported 38.54% had LSI greater than > 96.5% and 61.35% <96.5% following ACLR at six months. Furthermore, Gokeler et al. (2016) reported 35.3% achieved a strength score greater than >3.1 N.m.kg^{-1} at six months post ACLR, which again is similar to this study. Considering this relative level of quadriceps strength, both Gokeler et al. (2016) and Pietrosimone et al. (2016) proposed >3.0N.m.kg^{-1} quadriceps strength. Still, in the current study, the ACLR group at six did not meet the criteria. However, Gokeler et al. (2016) utilised concentric contractions of quadriceps and hamstring with a velocity of 60º/s, 180º/s and 300º/s on a twenty-eight patient (22 males and six females) following ACLR at 6.5 months postoperatively. Furthermore, Pietrosimone et al. (2016) utilised isometric contractions of quadriceps muscles at the angle of 90º on 96 patients (34 males, 62 females) following ACLR at six months postoperatively. The results of Gokeler et al. (2016) and Pietrosimone et al. (2016) reported only 35.7% of the patients passed criterion for normalised quadriceps peak torque (>3.0 N.m.kg^{-1}) as opposed to Pietrosiomone et al. (2016) said only 30 patients passed benchmark for the relative level of peak torque quadriceps. In the current study, the mode of eccentric and concentric contractions used which, the patients in the present study found challenging to perform due to fear of pain and fear of a load of isokinetic knee test (velocity 60º/s). Therefore, the mode of contractions in the present study was more challenging for patients to perform a comparison to studies by Gokeler et al. (2016) and Pietrosimone et al. (2016) that, the mode of their contractions was more comfortable to perform. This demonstrates that across multiple studies ACLR patients appear to be failing to achieve a satisfactory level of strength (as defined by Pietrosimone et al 2016) and so therapists involved in rehabilitating these patients need to consider appropriate means to change rehabilitation protocols to start to achieve this target. This deficit in the quadriceps strength and limb asymmetry index if not addressed might be related to long term ongoing knee symptoms, knee OA, recurrent ACL injury (either contralateral or graft rupture).

Comparing the injured limb between the ACLR group at three and six months

The normalised reach distance for YBT for ACLR from three to six months did not improve significantly ($p>0.005$) with a small ES (.23) (Table 7). Considering SLHD, there was no significant difference between injured limb from three to six months following ACLR with small ES (.23) (Table 7), so again that does not appear to have improved. The quality of landing (2D FPPA and QASLS) during SLS and SLHD has improved from three to six months following ACLR significantly between the injured limbs of ACLR (Table 2). Though this should be viewed with some caution as there were only small ES for 2D FPPA and QASLS during SLS and medium ES for 2D FPPA and QASLS during SLHD for injured limbs of ACLR from three to six months.

There was no significant difference ($p>0.005$) from three to six months in normalised peak torque for concentric contraction of quadriceps and eccentric contraction of the hamstring. with a small ES (0.16), suggesting there were no real performance differences between injured limb from three to six months. However, there was a significant difference ($p<0.005$) from three to six months in normalised peak torque for the eccentric contraction of quadriceps and concentric contraction of the hamstring following the ACLR. though this had a small ES (Table 7).

Regarding the KOOS subscales, there was significantly different ($p<0.005$) between ACLR patients from three to six months for KOOS (symptoms and sport) (Table 7), with small and medium ES, suggesting there were real differences between injured limbs. There were no significant differences ($p>0.005$) in KOOS (pain, ADL and QOL) between the ACLR patients from three to six months (Table 7), with small ES suggesting there were, in fact, no real differences for KOOS (pain, ADL and QOL) (Table 7).

When examining the cut off values for the KOOS/QOL and TSK in the present study, neither of the values passed QOL>81 (Barenius et al. 2013) and TSK> 4 points from three to six months following ACLR (Table 3). The level of fear (TSK score) of the ACLR group from three to six months increased, this might have been possibly because of the expectation of the ACL injured players to return to play at six months. Also, the cutoff values for the isokinetic knee strength was increased from three to six months in terms of the LSI>100 and normalised peak torque >3.1 $N.m.kg^{-1}$. Two systematic reviews by Forster and Forster (2005) and Li et al. (2012) compared BPTB autograft versus HT autograft. Forster and Forster (2005) and Li et al. (2012) found that BPTB autograft is associated with more significant stability than HT autograft. However, there is no difference in clinical knee scores and rate of failure. Considering the effect of an autograft of HT and BPTB on the quadriceps strength, Spindle et al. (2004) found no difference in quadriceps isokinetic strength measurements between HT and BPTB in the systematic review of 7 randomised controlled trials. Gobbi and Francisco (2006) followed 100 patients after ACLR for two years to determine their ability to return to sport. Gobbi and Francisco found no difference between HT and BPTB groups concerning the ability to return to sports. The quality of landing during SLHD at six months had still not improved compared to the control group. Therefore, when most of the ACL injured players failed to pass the criterion at six months post ACLR, the fear of not joining the team and possibly missing essential matches harmed the level of confidence.

The current study's potential limitation included not testing all participants at the three-time points (ACLD, ACLR at three and six months postoperatively). Therefore, the present study determined whether the normalised peak torque for both the hamstring and quadriceps cutoff values will meet at specific later time points. Other potential limitations also include using post hoc analysis instead of a priori analysis in the present study. When analysed the current research data, there was a significant difference between the means of the ACLR (three and six months) and the control group with the existing sample size. Post hoc analysis was also an essential procedure for multiple variables comparison testing to control for type 2 error data and render the chance of discovering false positives unacceptably high. The potential limitation also includes not matching the leg length and body mass of the control group to the ACLR group apriori. Therefore, it is unclear whether the results would be different compared to the control group's leg length and body mass with the ACLR group.

Conclusion

The tests used in the current study were safely employed on both the ACLR group at three and six months and the control group. Outcome measurement is an essential tool in sports exercise science and medicine. It can be used to assess, evaluate, and justify training methods, treatment, and rehabilitation interventions through the identification of an athlete's ability to cope with the physical demands placed upon them. In the current study, two-time points used because most athletes following ACLR would return to running at three months and return to sports at six months postoperatively (Herrington et al 2013). Further, in the current study, all patients at three months met the criteria (YBT>90%, SLHD >70%, LSI >70% for both hamstring and quadriceps strength, no effusion, full knee ROM, symmetrical gait pattern before return to running. However, the quality of landing (2D FPPA and QASLS) during SLS and SLHD was poor compared to the control group, suggesting more neuromuscular rehabilitation exercise would be recommended before introducing more demanding loads such as change of direction and plyometric drills. The primary finding was the poor outcome in quadriceps strength following ACLR at six months, with 26% achieved the relative peak torque value >3.1N.m.kg^{-1}. Further, the poor outcome in quadriceps following ACLR at six months should delay athletes return to competitive sports until the deficit in the quadriceps restored. The quality of landing during SLS and SLHD improved from three to six months in the ACLR group (though with small effect size), but the control group still perform better quality of landing during the unilateral task. Therefore, the patient in the current study should still continue to focus on strengthening the quadriceps and hamstring muscle along with neuromuscular drills to address the knee muscular deficit and the quality of landing beyond this 6-month time marker. Because the quality of movement performance is equally as important as quantity, and performance-based tests that allow the clinician to assess both aspects would appear to be equally important in dictating outcome (see chapter 2), which is a significant finding of this study with some quantity markers being reached e.g., hop distance with the absence of a quality to that performance which could leave the athlete vulnerable to future injury. This information is useful for decision-making regarding return to running (RTR), and for further progressions during rehabilitation (e.g., commencing sport-specific training). Therefore, it seems reasonable to suggest that quality decision-making regarding functional progressions in rehabilitation (including RTR) should be individualised and based on a test battery comprising multiple criteria including function (quantity and quality), strength and time.

Chapter 5

Consistency of test performance of male patients following anterior cruciate ligament reconstruction (ACLR) at three and six months post operatively

Summary

The first aim of this chapter was to establish the relative reliability (ICC (3,1) and 95% confidence interval) and absolute reliability (standard error of measurement) for the KOOS, TSK, YBT, isokinetic knee strength test, 2D FPPA during SLS and SLHD and QASLS during SLS and SLHD for the ACLR patients at three months and the control group. The second aim of this study was to establish relative and absolute reliability for the same tests for the ACLR at six months and the control group. The third aim of this study was to compare the relative and absolute reliability of the same tests between the ACLR patients at six months to three months post-operation. The findings of the current study demonstrated that the ICCs for the YBT and SLHD were high for both the control and the ACLR group at three months. Further, the control group showed higher ICCs in the TSK, KOOS, isokinetic knee flexor and extensor with the mode of concentric and eccentric contractions for both quadriceps and hamstring muscles and QASLS during SLHD compared to the ACLR at three months. However, the ICCs for the control group was lower for 2D FPPA during SLS and SLHD and QASLS during SLS compared to the ACLR at three months. The findings in the current study demonstrate that the ICCs for the YBT and TSK were high for both the control and the ACLR group at six months. Also, the control group showed higher ICCs in the SLHD, KOOS, isokinetic knee flexor and extensor (eccentric contractions) for both quadriceps and hamstring muscles and concentric contraction of hamstring compared to the ACLR at six months. However, the ICCs for the control group was lower for 2D FPPA during SLS and SLHD and QASLS during SLS on the non-injured limb compared to the ACLR at six months.

The control group achieved more consistency in a number of tests in this study, including SLHD, isokinetic knee strength, KOOS and TSK compared to the ACLR patients. The least reliable test performance was seen in the isokinetic knee strength test, QASLS during SLSH, KOOS and TSK for the ACLR patients at three months in terms of the ICCs and SEM values. However, the consistency of performance of the isokinetic knee strength, QASLS during SLHD, and TSK improved from three to six months in the ACLR patients.

Introduction

Injury to the ACL is a common knee injury sustained by athletes (Ardern et al., 2015; Ithurburn et al., 2017; Nagelli and Hewett 2017) that typically requires surgical reconstruction of the ACL to restore mechanical knee stability (Frobell et al. 2010). Outcomes after primary ACLR are considered to be suboptimal due to multiple factors (Losciale et al. 2019). The rate of return to the sport in a cohort study of multi-sport athletes (992 male, 448 female) who resumed their sports by twelve months following primary ACLR who were aged 25 years and younger was 48%, in athletes (26-35 years old) it was 32% and in those more aged more than 36 years old 19% (Webster and Hewett 2018). The incident of second ACL injury is reported to be as high as 32% in athletes younger than 18 years (Dekker et al. 2017) and 23% in athletes 25 years or younger (Wiggins et al. 2016). Considering an overall rate of ACL graft rupture, Wright et al. (2011) stated 5.8%, and contralateral ACL rupture rate was 11.8% at minimum five years follow up. Culvenor et al. (2014) reported 47% had patellofemoral joint and 31% tibiofemoral joint osteoarthritis after hamstring tendon autograft following ACLR in 70 subjects with mixed male and female subjects within 5-10 years follow up.

Fear of re-injury is one of the most frequent reasons cited by athletes for not returning to their pre-injury level of sports after ACLR (Ardern et al., 2015). As up to one in two athletes who do not return to sports report that the main reason is fear of sustaining a new injury (Ardern, Osterberg, Tagesson, Gauffin, Webster and Kvist, 2014; Flanigan, Everhart, Pedroza, Smith and Kaeding, 2013).

These poor outcomes have prompted to clinicians and researchers to establish multidimensional approaches to outcome measurement across a wide range of subjective, objective, bio-psychosocial factors along with the quality of movement tasks to reduce the risk of poor outcomes by attempting to improve decision making around the patients' readiness to return to sport and even higher-level activities. Despite the research attention on this, it is still unclear what the critical tests are and when even testing is undertaken, it does not always predict a successful outcome. A reason for this could be that what has not been established is the reliability of these outcome measurements in the population concerned that is in an ACLR cohort. For practitioners to confidently perform KOOS, TSK, YBT, 2D FFPA and QASLS during SLS and SLHD, and isokinetic knee strength tests on an adult male population from Middle Eastern region, the relative (ICC and 95% confidence interval) and absolute reliability (standard error of measurement) of the measurement procedure must be known. Portney and Watkins (2009) stated that reliability is the ability of a measurement procedure to generate consistent values. Further, Portney and Watkins (2009) stated that measurement precision is the ability of a measurement procedure to yield exact values. Studies by Batterham and George (2003) and Clark et al. (2016) stated that the lack of reliability and measurement precision undermine the validity of raw data and compromise data analysis procedures and practitioners' decision-making. Therefore, it is imperative to establish test-retest reliability between session with SEM and 95% CI to monitor if true changes have occurred or what is being reported is masked with noise or measurement error.

Several factors can influence the reliability of a test. These can be broadly grouped into random error and systematic bias. Random error is the 'noise' in a measurement, typically seen as within-subject variation, inconsistencies in the measurement protocol or the examiner's measurements (Atkinson and Nevill, 1998 and Tyson, 2007). Systematic bias refers to a trend for measures to be different due to learning effects or fatigue (Atkinson & Nevill, 1998 and Batterham & George, 2003). Further, the systematic bias relates to the testing threat to internal validity, whereby the pre-test can influence the values obtained on the post-test (Batterham and George, 2003). To assess the systematic bias, the calculation of the mean (average) value for each of the trials permits an initial screen for any large systematic bias. Further, to prevent the large systematic bias during tests, the subject should fully be familiarised with the test that any learning effect was relatively complete (Batterham and George, 2003).

Single Leg Hop Distance (SLHD)

The single leg hop for distance is the most frequently used, with 90% or higher limb symmetry indices (LSI) being the most well-accepted current standard for a successful test (Dingenen & Gokeler, 2017 and Grindem et al. 2016). Athletes who do not meet the discharge criteria before returning to professional sports have a four times greater risk of sustaining an ACL graft rupture compared with those who met RTP criteria (Kyritsis et al. 2016). When considering test-retest reliability on ACLR patients, two studies by Reid et al. (2007) and Gustavsson et al. (2006) reported reliability, reporting good to excellent (ICC=0.82-0.97) in ACLD knees and following ACLR at four and six months along with SEM ranging from 3.04% to 5.59% and SDD ranged from 7.05% to 12.96% of leg length. Considering test-retest reliability on healthy subjects, two studies by (Booher et al. (1993) and Munro et al. (2012) reported (ICC= 0.55-0.91) along with SEM ranged from 2.72 cm to 3.01 cm, and SDD ranged from 7.54 cm to 8.93 cm.

Isokinetic knee strength test

Two studies by Impellizzeri et al. (2008) and Sole et al. (2007) reported excellent reliability ranged from (ICC=0.92-0.98) within a day and between day along with SEMs ranged from (4.3-11.2 Nm) with the mode of concentric and eccentric contraction on healthy subjects. However, both studies by Impellizzeri et al. (2008) and Sole et al. (2007) reported reliability on healthy subjects. No study would appear to have reported reliability of testing in an ACL population.

2D FPPA during SLS and SLHD

Two-dimensional video analyses are less expensive, portable and easy to use equipment to measure knee valgus angle in athletes, general, and injured populations (Willson and Davis, 2008; Noyes et al. 2005 and Munro et al. 2012). Munro et al. (2012) reported Within-day (ICC=0.55-0.88), between-days (ICC= 0.72-0.91) reliability, measurement error values (SEMs= 2.72-3.01 degree) and minimal detectable differences values (SDD= 7.54-8.93 degree) for 2D FPPA on 22 healthy subjects (M=11, F=11) only.

Y Anterior Reach Balance Test (YBT)

The YBT was modified from SEBT by Plisky et al. (2009) for the intent of improving test repeatability. Both SEBT and YBT have been shown to be predictive of lower extremity injuries in athletes (Butler et al., 2013; Chimera et al., 2016; Gonell et al., 2015; Plisky et al., 2006; Smith et al., 2015). Three studies by Dobija et al. (2018); Munro et al., (2010) and Plisky et al. (2009) reported good to excellent reliability of SEBT (ICC=0.88-0.96) in ACLD knee and healthy subjects (ICC=0.99-1.00). However, test-retest reliability of SEBT alongside SEM and SDD following ACLR at three and six months has not been reported yet.

Patient Report outcomes (PROs)

Woby, Roach, Urmston and Watson, (2005) stated the good Intraclass correlation coefficient (ICC) of the TSK and short version of TSK-11 (TSK: ICC=0.82, Standard error of measurement (SEM) 3.16; TSK-11: ICC=0.81, SEM= 2.54, good internal consistency (TSK: a=0.76; TSK-11: a=0.79). Further, Woby, Roach, Urmston and Watson, (2005) reported cutoff scores on patients with chronic lower back pain. Therefore, fear of re-injury or fear of movement is an important modifiable risk factors following

ACLR, and it requires attention to assist patients with ACL deficient knee and following ACLR to return to daily activity of life and their pre-injury level of sports.

High reliability (ICC, SEMs) of the KOOS subscales; pain (ICC =0.93; SEM= 2.2), Symptoms (ICC=0.85; SEM=3.1), activity of daily living (ICC=0.9; SEM=2.1), function in sports and recreation (ICC=0.75; SEM=2.1), and knee related quality of life (ICC=0.89; SEM=2.6) in fifty seven athletes (male=39, female= 18, age =25.6 years) is reported after 7.6 months ACLR, and the small detectable changes (SDD) ranges from 6.1 to 8.5 points (Salavati, Akhbari, Mohammadi, Mazaheri and Khorami, 2011).

No study has reported the relative and absolute reliability for the KOOS, YBT, 2D FPPA and QASLS during SLS and SLHD and isokinetic knee flexor and extensor muscle strength with the mode of the concentric and eccentric contraction on an adult male population from Middle East region following ACLR at three and six months postoperatively (or any other ethnic group for that matter). Knowledge of relative and absolute reliability for both limbs (injured and non-injured) are essential following the ACLR. Because if the relative and absolute reliability are different between injured and non-injured limbs; good reliability for one limb and poor reliability for the other limb can result in flawed data analysis, especially if using metrics such as limb symmetry index.

The aim of this study was to identify the reliability of a series of tests used to quantify outcome from ACLR. This is essential to understand in order to contextualise any findings in light of the meaningful differences between data generated at different time points, establishing if the differences are real and beyond measurement error. There are three objectives for this study. The first objective of this chapter was to establish the relative reliability ($ICC_{3,1}$ and 95% confidence interval) and absolute reliability (standard error of measurement) for the KOOS, TSK, YBT, isokinetic knee strength test, 2D FPPA during SLS and SLHD and QASLS during SLS and SLHD for the ACLR at three months and control group. Further, to compare the relative and absolute reliability between the control and the ACLR group at three months postoperatively to on an adult male from the Middle Eastern population. It was hypothesised that the control group would achieve higher relative reliability and lower SEM compared to the ACLR at three months. The second objective of this study was to establish relative and absolute reliability for the same tests for the ACLR at six months and control group. Further, to compare the relative and absolute reliability between the control and the ACLR at six months postoperatively. Also, it was hypothesised that the control group would achieve higher relative reliability and lower SEM compared to the ACLR group at six months. The third objective of this study was to compare the relative and absolute reliability of the same tests between the ACLR at six months to three months. It was hypothesised that the ACLR group at six months would achieve higher relative reliability and lower SEM compared to the ACLR group at three months.

Method

Participants

ACL injured group: Twenty recreationally active participants, all male (age 25.50 ± 4.35 years, height 170.37 ± 39.89cm, weight 76.60 ± 8.51kg) (Table 1), all of whom were part of Alahli sports club squad, and part of Up and Running sports medicine clinic in the United Arab of Emirates, volunteered for the study. The same inclusion and exclusion criteria, approval and consent procedures were used as previously outlined in chapter 3. All tests were undertaken at 3 and 6 months post operatively with a second series of tests following the first one week later.

Control group: Twenty-seven male control subjects (age 25.67±4.95 years, height 168.52±8.95 weight 59.22±8.70) (Table 1), all of whom were part of Alahli sports club squad, and part of Up and Running sports medicine clinic in the United Arab of Emirates, volunteered for the study. The same exclusion criteria, approval and consent procedures were used as previously outlined in chapter 3. All tests were undertaken of two occasions one week apart.

Procedures

The same procedures for patient report outcomes (KOOS, TSK), YBT, single leg squat (SLS), single leg hop for distance (SLHD), isokinetic knee flexors and extensors, 2D frontal plane projection angle and qualitative score sheet (QASLS) during SLS and SLHD were used as previously outlined in chapter 3.

Table 1: Descriptive data of included subjects for control group and ACLR at three and six months postoperatively (Mean± Standard deviation).

	ACLR 3&6 months (n=20)	Control group (n=27)
Age (years)	25.5±4.35	25.6±4.95
Height (cm)	170.3±39.89	168.5±8.95
Mass (kg)	76.6±8.51	59.2±8.70
Sex(male/female)	20/0	27/0
Leg length (%)	93.5±4.7	87.81±5.31
Sports (number)		
Basketball	5	8
Handball	2	5
Volleyball	5	7
Football	8	7
Limb dominance (right/left)	15/5	7/20
Injured limb (right/left)	16/4	N/A
Autograft (BPTB/Hamstring)	7/13	N/A
Mean time from injury to ACLR surgery(days)	±32	

Statistical Analysis

Statistical analysis was performed in SPSS for Mac OS (IBM, New York, NY, USA) for the normality and ICC calculations. Normality of all data was inspected using a Shapiro–Wilks test for retest session for the ACLR and the control group. The model of $ICC_{3,1}$ was chosen as the mean of three trials from a single rater were used (Shrout and Fleiss 1979). The difference between the model $ICC_{3,1}$ and $ICC_{3,k}$ is that the $ICC_{3,1}$ assessed from a single rater and the reliability calculated from a single measurement. The reliability of the $ICC_{3,k}$ is calculated by taking an average of the k raters' measurements which was inappropriate for this study as only a single rater was used (McGraw and Wong 1996). Relative reliability was assessed by ($ICC_{3,1}$) and 95% confidence interval (CI) (Denegar & Ball, 1993; Portney & Watkins, 2009) and the ICC values are interpreted according to the following criteria poor <0.40, fair = 0.40 – 0.70, good = 0.70 – 0.90 and excellent >0.90 (Coppieters et al.2002). Absolute reliability was assessed by the standard error of measurement (SEM) (Atkinson & Nevill, 1998; Denegar & Ball, 1993). The SEM was calculated using the formula: SD (pooled) * (√ (1- ICC) (Thomas et al. 2005) utilising the standard deviation (SD) and reliability coefficient (i.e., the ICC) of the measured sample. Also, homoschedascity was inspected.

Results

No subjects for ACLR and control group experienced pain during testing on day one or day two, and there were no adverse effects. All data were normally distributed for the ACLR group at three and six months postoperatively and the control group ($P>0.05$).

Compare relative and absolute reliability between the control group and the ACLR group at three months.

The ICC $_{(3,1)}$ values and 95% confidence intervals, and SEM values for the control group (Table5) and the ACLR group at three months (Table 4) are reported. The good to excellent ICC (ranged from 0.86-0.98) and low SEM (ranged from 5.37-6.01 LL%) are shown for YBT for both the control group and the ACLR patient at three months. The good to excellent ICC (ranged from 0.87-0.94) for the ACLR at three months and good ICC (0.75) for the control group with different SEM for the control (28.60 LL%) and the ACLR at three months (ranged from 18.59-21.54 LL%) shown during SLHD. The good to excellent ICC (ranged from 0.79-0.97) for ACLR at three months and fair to good ICC (0.57-0.85) for the control group with different SEM (control=1.8°-2.6° and ACLR at three months=3.4°-6.4°) shown for FPPA during SLS and SLHD. The poor to good ICC (ranged from 0.27-0.72) for ACLR at three months and fair ICC (ranged from 0.43-0.54) for the control group with different SEM (control=0.45-0.66 and ACLR at three months=0.37-0.96) shown for QASLS during SLS and SLHD. The fair to excellent ICC (ranged from 0.56-0.93) for the control group and poor to fair ICC (ranged from 0.15-0.69) for the ACLR group at three months with different SEM (control=0.24-0.56 $N.m.kg^{-1}$ and ACLR at three months=0.20-0.43 $N.m.kg^{-1}$) shown for isokinetic knee strength test for flexors and extensors with the mode of concentric and eccentric contractions. The good to excellent ICC (ranged from 0.83-0.94) for the control group and poor to fair ICC (ranged from 0.15-0.43) for the ACLR group at three months with different SEM (control=5.80-12.00 and ACLR at three months=5.76-16.42) shown for the KOOS subscales. The good ICC (0.83) for the control group and poor ICC (0.06) for the ACLR group at three months with different SEM (control=4.46 and ACLR at three months=3.42) shown for TSK.

Compare relative and absolute reliability between the control group and the ACLR group at six months.

The ICC $_{(3,1)}$ values and 95% confidence intervals, and SEM values for the control group (Table 5) and the ACLR group at six months (Table 4) are reported. The good to excellent ICC (ranged from 0.85-0.98) and low SEM (ranged from 6.01-6.80 LL%) shown in YBT for both the control group and the ACLR at six months. The fair ICC (ranged from 0.47-0.63) for the ACLR at six months and good ICC (0.75) for the control group with different SEM for the control (28.60 LL%) and the ACLR at six months (ranged from 21.16-22.10 LL%) shown during SLHD. The excellent ICC (ranged from 0.90-0.98) for ACLR at six months and fair to good ICC (0.57-0.85) for the control group with different SEM (control=1.8°-2.6° and ACLR at six months=2.4°-4.4°) shown for FPPA during SLS and SLHD. The fair to good ICC (ranged from 0.46-0.74) for ACLR at six months and fair ICC (ranged from 0.43-0.54) for the control group with different SEM (control=0.45-0.66 and ACLR at six months=0.45-0.79) shown for QASLS during SLS and SLHD. The fair to excellent ICC (ranged from 0.56-0.93) for the control group and fair to good ICC (ranged from 0.56-0.84) for the ACLR group at six months with different SEM (control=0.24-0.56 $N.m.kg^{-1}$ and ACLR at six months=0.31-0.46 $N.m.kg^{-1}$) shown for isokinetic knee strength test with the mode of concentric and eccentric contractions. The good to excellent ICC (ranged from 0.83-0.94) for the control group and poor to fair ICC (ranged from 0.20-0.70) for the ACLR group at six months with different SEM (control=5.80-12.00 and ACLR at six months=5.66-16.99) shown for the KOOS subscales. The good ICC (0.83) for the control group and good ICC (0.89) for the ACLR group at six months with similar SEM (control=4.46 and ACLR at six months=4.48) shown for TSK.

Compare relative and absolute reliability between the ACLR group at three and six months.

The ICC $_{(3,1)}$ values and 95% confidence intervals, and SEM values for the ACLR group at three and six months (Table 4) are reported. The good to excellent ICC (ranged from 0.85-0.94) and low SEM (ranged from 5.37-6.80 LL%) shown in YBT for both ACLR groups at three and six months. The fair ICC (ranged from 0.47-0.63) for the ACLR at six months and good to excellent ICC (ranged from 0.87-0.94) for the ACLR group at three months with different SEM for the ACLR at six months (ranged from 21.16-22.10 LL%) and the ACLR at three months (ranged from 18.59-21.54 LL%) shown during SLHD. The excellent ICC (ranged from 0.90-0.98) for the ACLR at six months and good to excellent ICC (0.79-0.97) for the ACLR group at three months with different SEM (ACLR at three months=3.4°-6.4° and ACLR at six months=2.4°-4.4°) shown for FPPA during SLS and SLHD. The fair to good ICC (ranged from 0.46-0.74) for ACLR at six months and poor to good ICC (ranged from 0.27-0.72) for the ACLR group at three months with different SEM (ACLR at three months=0.37-0.96 and ACLR at six months=0.45-0.79) shown for QASLS during SLS and SLHD. The poor to fair ICC (ranged from 0.12-0.69) for the ACLR group at three months and fair to good ICC (ranged from 0.56-0.84) for the ACLR group at six months with different SEM (ACLR at three months=0.20-0.43 $N.m.kg^{-1}$ and ACLR at six months=0.31-0.46 $N.m.kg^{-1}$) shown for isokinetic knee strength test with the mode of concentric and eccentric contractions. The poor to fair ICC (ranged from 0.15-0.43) for the ACLR group at three months and poor to fair ICC (ranged from 0.20-0.70) for the ACLR group at six months with different SEM (ACLR at three months=5.76-16.42 and ACLR at six months=5.66-16.99) shown for the KOOS subscales. The poor ICC (0.06) for the ACLR group at three months and good ICC (0.89) for the ACLR group at six months with different SEM (ACLR at three months=3.42 and ACLR at six months=4.48) shown for TSK.

Table 2: Mean and standard deviation (SD) for the ACLR group (three and six months) and the control group between sessions (test-retest) for YBT, SLHD, 2D FPPA° (SLS and SLHD) and QASLS (SLS and SLHD) tasks and normalised peak torque ($N.m.kg^{-1}$) for quadriceps and hamstring muscles. The distance hopped was normalized to a percentage of leg length (distance from anterior superior iliac spine to medial malleolus) and multiplying by 100.

	Mean day 1						**Mean day 2**						**SD day 1**						**SD day 2**					
	IN3	**NI3**	**IN6**	**NI6**	**DCTRL**	**NDCTRL**	**IN3**	**NI3**	**IN6**	**NI6**	**DCTRL**	**NDCTRL**	**IN3**	**NI3**	**IN6**	**NI6**	**DCTRL**	**NDCTRL**	**IN3**	**NI3**	**IN6**	**NI6**	**DCTRL**	**NDCTRL**
YBT (%)	60.69	62.08	64.85	64.90	65.70	67.66	61.69	64.40	67.00	66.33	67.87	68.02	5.62	5.16	7.14	7.52	6.06	5.30	5.90	5.68	6.16	6.55	6.14	5.35
SLHD (%)	150.68	168.71	128.97	132.02	118.01	121.31	156.84	176.97	144.57	145.48	120.60	122.42	21.80	19.30	29.34	24.72	26.61	28.63	21.89	18.22	26.67	26.44	27.80	28.90
FPSLS°	23	21	20	18	17	17	22	20	19	18	16	17	4	5	3	3	3	3	4	4	3	2	3	2
FPSLHD°	25	22	21	18	17	17	23	20	20	18	15	16	6	7	5	5	3	2	5	7	5	5	2	2
QLSLS	5	4	4	3	4	3	4	4	3	3	3	3	1	1	1	1	1	1	1	1	1	1	1	0
QLSLHD	5	4	3	3	4	3	4	4	3	3	3	3	1	1	0	1	1	1	1	1	0	0	1	1
PTQC ($N.m.kg^{-1}$)	2.22	2.57	2.23	2.53	1.57	1.74	2.37	2.51	2.33	2.48	1.58	1.66	.92	.40	0.46	0.40	0.43	0.51	.50	.50	0.50	0.50	0.45	0.40
PTQE ($N.m.kg^{-1}$)	1.50	1.57	2.00	2.17	1.51	1.67	1.92	2.03	2.15	2.25	1.59	1.71	.49	.24	0.50	0.48	0.53	0.57	.38	.44	0.53	0.53	0.63	0.64
PTHC ($N.m.kg^{-1}$)	2.55	2.76	1.78	1.92	1.64	1.72	2.39	2.46	1.91	2.01	1.63	1.73	.45	.33	0.50	0.44	1.63	1.73	.58	.57	0.55	0.58	0.30	0.31
PTHE ($N.m.kg^{-1}$)	1.71	1.75	1.93	2.05	1.77	1.88	1.88	1.97	1.93	2.03	1.81	1.91	.60	.25	0.43	0.44	0.43	0.44	.32	.34	0.52	0.55	0.42	0.43

Percentage of leg length (LL%)= (distance hopped (cm) ÷ leg-length (cm) x 100.; 2D frontal plane projection angle for single leg squat (FPSLS°) and single leg hop for distance (FPSLHD°), Qualitative analysis loading for single leg squat (QSLS) and single leg hop for distance (QSLHD); Injured limb (IN); Non-injured limb (NI) and Standard deviation (SD), DCTRL= dominant side of the control group, NDCTRL= non-dominant side of control group; Normalised peak torque quadriceps concentric contraction (PTQC); Normalised peak torque quadriceps eccentric contraction (PTQE); Normalised peak torque hamstring concentric contraction (PTHC); Normalised peak torque hamstring eccentric contraction (PTHC).

Table 3. Mean and Standard deviation (SD) for the ACLR group (three and six months) and the control group between sessions (test-retest) for KOOS and TSK.

	Mean day 1			**Mean day 2**			**SD day 1**			**SD day 2**		
	ACLR3	**ACLR6**	**CTRL**	**ACLR3**	**ACLR6**	**CTRL**	**ACLR3**	**ACLR6**	**CTRL**	**ACLR3**	**ACLR6**	**CTRL**
KOOS-Pain	83.09	88.98	92.59	82.78	92.8	93.83	5.76	9.74	10.20	6.02	4.87	7.87
KOOS-Symptoms	61.07	70.51	65.85	78.74	63.04	66.19	7.13	11.36	6.96	10.22	5.34	5.69
KOOS-ADL	85.29	92.61	94.37	84.77	95.05	95.99	5.64	6.63	8.17	6.61	4.25	5.51
KOOS-Sport	48.06	65.5	88.70	48.56	75.75	91.30	16.48	21.02	14.58	16.58	10.04	9.47
KOOS-QOL	49.9	63.75	86.48	50.51	76.56	87.96	8.12	24.55	12.67	8.10	12.15	9.95
TSK	34.35	31.3	35.19	32.10	29.80	33.41	3.72	4.93	4.52	3.39	4.25	4.53

KOOS-Pain= knee osteoarthritis outcome score for the pain subscale; KOOS-symptoms= knee osteoarthritis outcome score for the symptom's subscale; KOOS-ADL= knee osteoarthritis outcome score for the activity daily living; KOOS-sport= knee osteoarthritis outcome score for sport; KOOS-QOL= knee osteoarthritis outcome score for the quality of life; TSK=Tampa scale kinesiophobia; CTRL= dominant side of the control group.

Table 4. Relative reliability (ICC $_{(3,1)}$ and 95% CI) and absolute reliability (SEM) between sessions (test-retest) during YBT, SLHD, isokinetic knee strength, 2D FPPA° and QASLS during SLS and SLHD, KOOS and TSK following ACLR at three and six months.

	ACLR at three months			ACLR at six months		
	ICC (3,1)	ICC (3,1) 95% CI	SEM	ICC (3,1)	ICC (3,1) 95% CI	SEM
ANTIN (LL%)	0.94	0.69-0.98	5.73 (LL%)	0.85	0.53-0.94	6.33 (LL%)
ANTNI (LL%)	0.86	0.14-0.96	5.37 (LL%)	0.92	0.76-0.97	6.80 (LL%)
SLHIN (LL%)	0.94	0.32-0.98	21.54 (LL%)	0.47	0.06-0.75	21.16 (LL%)
SLHNI (LL%)	0.87	0.05-0.96	18.59 (LL%)	0.63	0.19-0.84	22.10 (LL%)
PTQCIN ($N.m.kg^{-1}$)	0.63	0.31-0.82	0.39 ($N.m.kg^{-1}$)	0.61	0.26-0.82	0.38 ($N.m.kg^{-1}$)
PTQCNI ($N.m.kg^{-1}$)	0.53	0.15-0.77	0.33 ($N.m.kg^{-1}$)	0.65	0.32-0.84	0.31 ($N.m.kg^{-1}$)
PTHEIN ($N.m.kg^{-1}$)	0.69	0.17-0.88	0.29 ($N.m.kg^{-1}$)	0.56	0.16-0.80	0.36 ($N.m.kg^{-1}$)
PTHENI ($N.m.kg^{-1}$)	0.29	0.06-0.60	0.20 ($N.m.kg^{-1}$)	0.57	0.17-0.80	0.37 ($N.m.kg^{-1}$)
PTHCIN ($N.m.kg^{-1}$)	0.63	0.31-0.82	0.43 ($N.m.kg^{-1}$)	0.71	0.39-0.87	0.41 ($N.m.kg^{-1}$)
PTHCNI ($N.m.kg^{-1}$)	0.45	0.04-0.72	0.38 ($N.m.kg^{-1}$)	0.74	0.46-0.88	0.45 ($N.m.kg^{-1}$)
PTQEIN ($N.m.kg^{-1}$)	0.15	0.10-0.56	0.21 ($N.m.kg^{-1}$)	0.70	0.39-0.87	0.44 ($N.m.kg^{-1}$)
PTQENI ($N.m.kg^{-1}$)	0.12	0.11-0.41	0.21 ($N.m.kg^{-1}$)	0.84	0.64-0.93	0.46 ($N.m.kg^{-1}$)
QAINSLS	0.48	0.09-0.78	0.80	0.46	0.10-0.78	0.79
QANISLS	0.72	0.42-0.87	0.96	0.74	0.36-0.89	0.67
QAINSLH	0.43	0.05-0.74	0.63	0.55	0.09-0.84	0.45
QANISLH	0.27	0.11-0.61	0.37	0.57	0.09-0.85	0.53
FPINSLS°	0.79	0.49-0.71	3.4°	0.90	0.14-0.97	2.7°
FPNISLS°	0.91	0.80-0.96	4.3°	0.95	0.89-0.98	2.4°
FPINSLH°	0.82	0.54-0.93	4.9°	0.98	0.82-0.99	4.3°
FPNISLH°	0.97	0.88-0.99	6.4°	0.98	0.93-0.99	4.4°
KOOS P	0.19	0.16-0.54	5.76	0.61	0.20-0.83	7.12
KOOS Symptoms	0.43	0.22-0.38	10.37	0.20	0.13-0.54	5.66
KOOS ADL	0.20	0.11-0.54	5.89	0.70	0.31-0.87	5.17
KOOS Sport	0.42	0.07-0.74	16.42	0.27	0.11-0.61	10.84
KOOS QOL	0.15	0.18-0.50	7.78	0.46	0.03-0.75	16.99
TSK	0.06	0.03-0.33	3.42	0.89	0.47-0.96	4.48

ANTRIN=anterior reach balance test injured limb; ANTRNI= anterior reach balance test non-injured limb; CI= confidence interval; SLHIN=single leg hop distance injured limb; SLHNI= single leg hop distance non-injured limb; FPSLSIN°= 2D frontal plane projection angle for single leg squat injured limb; FPSLSNI°= 2D frontal plane projection angle for single leg squat non-injured limb; FPSLHIN°= 2D frontal plane projection angle for single leg hop injured limb; FPSLHNI°= 2D frontal plane projection angle for single leg hop non-injured limb; QASLSIN= Qualitative analysis single leg squat injured limb ; QASLSNI= Qualitative analysis single leg squat non-injured limb; QASLHIN= Qualitative analysis single leg hop injured limb; QASLHNI= Qualitative analysis single leg hop non-injured limb; PTQCI=Normalised peak torque quadriceps concentric contraction injured limb; PTQCNI=Normalised peak torque quadriceps concentric contraction non-injured limb; PTQEI= Normalised peak torque quadriceps eccentric contraction injured limb; PTQENI= Normalised peak torque quadriceps eccentric contraction non-injured limb; PTHCI= Normalised peak torque hamstring concentric contraction injured limb; PTHCNI= Normalised peak torque hamstring concentric contraction non-injured limb; PTHEI= Normalised peak torque hamstring eccentric contraction injured limb and PTHENI= Normalised peak torque hamstring eccentric contraction non-injured limb.

Table 5. Relative reliability (ICC $_{(3,1)}$ and 95% CI) and absolute reliability (SEM) between sessions (test-retest) during YBT, SLHD, isokinetic knee strength, 2D FPPA° and QASLS during SLS and SLHD, KOOS and TSK for the control group.

Variables	ICC (3,1)	ICC (3,1) 95% CI	SEM
ANTD (LL%)	0.98	0.96-0.99	6.01 (LL%)
SLHD (LL%)	0.73	0.07-0.92	26.80 (LL%)
PTQCD (N.m.kg^{-1})	0.56	0.22-0.77	0.32 (N.m.kg^{-1})
PTHED (N.m.kg^{-1})	0.89	0.78-0.95	0.41 (N.m.kg^{-1})
PTHCD (N.m.kg^{-1})	0.70	0.43-0.85	0.24 (N.m.kg^{-1})
PTQED (N.m.kg^{-1})	0.89	0.78-0.95	0.56 (N.m.kg^{-1})
QASLSD	0.43	0.03-0.70	0.45
QASLHD	0.54	0.06-0.82	0.66
FPSLSD°	0.85	0.70-0.93	2.6°
FPSLHD°	0.57	0.19-0.79	1.8°
KOOS P	0.94	0.86-0.97	8.95
KOOS Symptoms	0.83	0.67-0.92	5.80
KOOS ADL	0.84	0.65-0.92	6.70
KOOS Sport	0.86	0.70-0.93	12.00
KOOS QOL	0.84	0.69-0.92	10.60
TSK	0.88	0.19-0.96	4.46

ANTD=anterior reach balance test dominant side; CI= confidence interval; SLHD=single leg hop distance dominant side; FPSLSD°= 2D frontal plane projection angle for single leg squat dominant side; FPSLHD°= 2D frontal plane projection angle for single leg hop dominant side; QASLSD= Qualitative analysis single leg squat dominant side; QASLHD= Qualitative analysis single leg hop dominant side; PTQCD=Normalised peak torque quadriceps concentric contraction dominant side; PTQED= Normalised peak torque quadriceps eccentric contraction dominant side; PTHCD= Normalised peak torque hamstring concentric contraction dominant side and PTHED= Normalised peak torque hamstring eccentric contraction dominant side.

Discussion

The first objective of this chapter was to establish the relative reliability (ICC $_{3,1}$ and 95% confidence interval) and absolute reliability (standard error of measurement) for the KOOS, TSK, YBT, isokinetic knee strength test, 2D FPPA during SLS and SLHD and QASLS during SLS and SLHD for the ACLR at three months and control group. Further, to compare the relative and absolute reliability between the control and the ACLR group at three months postoperatively in an adult male from the Middle Eastern population. It was hypothesised that the control group would achieve higher relative reliability and lower SEM compared to the ACLR at three months. The findings of the current study demonstrate that the control group showed higher ICCs in the TSK, KOOS, isokinetic knee flexor and extensor strength with the mode of concentric and eccentric contractions and QASLS during SLHD compared to the ACLR at three months (Table 4 & 5). However, the ICCs for the control group were lower for 2D FPPA during SLS and SLHD and QASLS during SLS compared to the ACLR at three months. Also, findings in the current study demonstrate that the ICCs for the YBT and SLHD were high for both the control and the ACLR group at three months. Findings also demonstrate that the control group showed lower SEM scores in 2D FPPA during SLS and SLHD, KOOS, QASLS during SLS and normalised peak torque for hamstring (concentric contraction) compared to the ACLR group at three months. However, the SEM for the control group was higher for SLHD, and normalised peak torque hamstring (eccentric contraction) compared to the ACLR at three months.

The second objective of this study was to establish relative and absolute reliability for the same tests for the ACLR at six months and control group. Further, to compare the relative and absolute reliability between the control and the ACLR at six months postoperatively. Also, it was hypothesised that the control group would achieve higher relative reliability and lower SEM compared to the ACLR group at six months. The findings of the current study demonstrate that the control group showed higher ICCs in the SLHD, KOOS, isokinetic knee flexor and extensor (eccentric contractions) for both quadriceps and hamstring muscles and concentric contraction of hamstring compared to the ACLR at six months (Table 4 and 5). However, the ICCs for the control group were lower for 2D FPPA during SLS and SLHD and QASLS during SLS on the non-injured limb compared to the ACLR at six months. Also, findings in the current study demonstrate that the ICCs for the YBT and TSK were high for both the control and the ACLR group at six months. Findings also demonstrate that the control group showed lower SEM scores in the SLHD, 2D FPPA during SLHD, KOOS (pain and QOL), QASLS during SLS, normalised peak torque (concentric and eccentric contraction) for hamstring muscle and concentric contraction for quadriceps muscle compared to the ACLR group at six months. However, the SEM for the control group was higher for QASLS during SLHD, normalised peak torque quadriceps (eccentric contraction) and KOOS/ADL compared to the ACLR at six months. The SEM values for the YBT, 2D FPPA during SLS, KOOS (symptoms and sport) and TSK were similar for the control and ACLR group at six months.

The third objective of this study was to compare the relative and absolute reliability of the same tests for the ACLR patients at six months and three months. It was hypothesised that the ACLR group at six months would achieve higher relative reliability and lower SEM compared to the ACLR group at three months. The findings of the current study demonstrate that the ACLR group at six months showed higher ICCs in the SLHD, KOOS (pain, ADL and QOL), isokinetic knee flexor and extensor (eccentric contractions) for both quadriceps and hamstring muscles and concentric contraction of hamstring, 2D FPPA on the injured limb during SLS and SLHD, QASLS on the non-injured limb during SLHD and TSK for both limbs compared to the ACLR at three months (Table 4). However, the ICCs for the ACLR group at six months were lower for the KOOS (symptoms and sport) compared to the ACLR at three months. Also, findings in the current study demonstrate that the ICCs for the YBT, normalised peak torque quadriceps with the mode of concentric contraction, 2D FPPA on the non-injured limb during SLS and SLHD, QASLS during SLS on both limbs and QASLS on the injured limb during SLHD were similar for both the ACLR group at three and six months. Findings also demonstrate that the ACLR group at six months showed lower SEM scores in the 2D FPPA during SLS on both limbs, 2D FPPA on the non-injured limb during SLHD, QASLS during SLS and SLHD on both limbs and KOOS (symptoms and sport) compared to the ACLR group at three months. However, the SEM for the ACLR group at six months was higher for the normalised peak torque quadriceps and hamstring (eccentric contraction) on both limbs, and concentric contraction for hamstring on the non-injured limb and KOOS (pain and QOL) compared to the ACLR at three months. The SEM values for the YBT, SLHD, normalised peak torque quadriceps with the mode of concentric contraction and KOOS/ADL were similar for both ACLR group at three and six months.

A direct comparison of the present data (Table 2-5) to previous literature is not possible because no other work has reported such data (KOOS, TSK, YBT, isokinetic knee strength test, 2D FPPA for two tasks (SLS and SLHD) and QASLS during (SLS and SLHD) on the ACLR group at three and six months for an adult male from United Arab of Emirates. The alternative is to compare the present data (Table 2-5) to values reported for other healthy adult male and recreational athletes and mixed-sex adult groups.

Comparison the relative and absolute reliability between the control group and the ACLR group at three months.

The good to excellent ICCs >0.70 was established during YBT and SLHD for both the control and ACLR at three months (Table 4&5). Therefore, one of the most important findings of the current study is that YBT and SLHD for the control and ACLR at three months can be used confidently in the clinical setting on different days. This is the first study to our knowledge to evaluate the test-retest reliability of YBT and SLHD in the ACLR male patients at three months.

An ICCs provide only a relative estimate of reliability, and a limited indication of the precision of the measurement (Denegar1993, Weir 2005). We also measured SEM and 95% CI to provide absolute measures of reliability, expressed in degree during 2D FPPA, normalised leg length (LL%) during Y anterior test, SLHD test and normalised peak torque/body mass: N.m.kg $^{-1}$ unit during isokinetic knee strength test. The determination of these outcomes allows clinicians to define whether changes in kinematic results at retest can be considered as real alterations in measurement beyond measurement error.

Considering the SEM for YBT, the SEM values for the dominant side of the control group (6.01 LL%) and the ACLR group at three months (injured side=5.73 LL% and non-injured side=5.37 LL%) were low, and 95% CI were similar for both the control and ACLR group at three months. Also, in the SLHD test, the SEM values for the dominant side of the control group (26.80 LL%) were slightly higher than the ACLR group at three months (injured side=21.54 LL% and non-injured side =18.59 LL%), but the 95% CI were similar for both the control and ACLR group at three months. Therefore, considering the relative and absolute reliability of the YBT and SLHD for both groups, both tasks were generated good to excellent relative reliability with low SEMs. Future research could, therefore, consider changes higher than 6cm for the YBT and 22cm for SLHD to be meaningful and beyond measurement error.

Considering the high to excellent reliability, studies by Dobija et al. (2018); Munro and Herrington, (2011) and Plisky et al. (2009) have found excellent reliability of SEBT (ICCs=0.88-0.96) in ACLD knee and healthy individuals. Considering agreement estimation, Dobija et al. (2018) has reported SEM and SDD on 33 ACLD patients compare with the 33-matched control group with mixed sexes. Furthermore, studies by Dobija et al. (2018); Munro and Herrington, (2011) and Plisky et al. (2009) applied the same model of ICC (3,1) to the present study. Still, the SEM values were higher (SEM> 8cm) in the study by Munro and Herrington (2011) and lower (SEM>3cm) for reviews by Dobija et al. (2018) and Plisky et al. (2009). Differences in SEM values were more than likely caused by the differences between SD scores across the studies (Dobija et al. 2018; Munro and Herrington, 2011 and Plisky et al. (2009) where SDs were much higher in the study by Munro and Herrington (2011) than the current one and lower by Dobija et al. (2019) and Plisky et al. (2009) than the present study. The SDs have a marked effect on the SEM values produced; this suggests that the SEM values for the current study are likely to be more accurate than Munro and Herrington (2011) because SD scores were much lower.

The fair to good ICCs was established for 2D FPPA during SLS and SLHD for the control group and good to excellent ICCs>0.70 for 2D FPPA during SLS and SLHD for the ACLR group at three months (Table 4 and 5). Considering the SEM values for 2D FPPA, the mean absolute value for the dominant side of the control group (SLS= 2.6° and SLHD= 1.8°) were lower than the ACLR group at three months during SLS (injured side=3.4° and non-injured side= 4.4°) and SLHD (injured side=4.9° and non-injured side= 6.4°). Furthermore, the 95% CI was higher for the ACLR group at three months compared to the control group suggesting that the ACLR at three months showed higher reliability by higher SEM than the control group. As explained in chapter four, the control group showed less knee valgus for 2D FPPA during SLS and SLHD compared to both limbs of the ACLR group at three months (Table 2). Also, the SDs for the control group was lower compared to the ACLR group at three months. Therefore, although the good to excellent ICCs reported for 2D FPPA during SLS and SLHD for the ACLR at three months, it seems that the ACLR group at three months showed poor performance with higher SEM, suggesting more neuromuscular rehabilitation exercise require to achieve better knee valgus during SLS and SLHD. Future research could, therefore, consider changes greater than 5-6 degrees to be meaningful and beyond measurement error.

When considering the reliability of the isokinetic strength testing of the knee flexors and extensors, the fair to excellent ICCs was established for the control group and the poor to fair ICCs for the ACLR at three months. The SEM value for the peak torque quadriceps with mode of concentric contractions for the dominant side control group (0.32 $N.m.kg^{-1}$) and the ACLR group at three months (injured side= 0.39 $N.m.kg^{-1}$ and non-injured side=0.33 $N.m.kg^{-1}$) were similar. Also, 95% CI were similar for both the control and the ACLR group at three months, suggesting there is no real different performance exist. Therefore, future research could consider changes greater than 0.40 $N.m.kg^{-1}$ for concentric quadriceps to be meaningful and beyond measurement error.

SEM values for the normalised peak torque hamstring with the mode of eccentric contraction for the control group (0.41 $N.m.kg^{-1}$) was higher than the ACLR group at three months (injured side= 0.29 $N.m.kg^{-1}$ and non-injured side=0.20 $N.m.kg^{-1}$). Also, the 95% CI were good to excellent for the control group and poor to good for the ACLR at three months, suggesting there is real difference exist in performance between two groups. Although the good ICCs>0.70 reported for the control group compared to the poor ICCs for the ACLR group at three months, there were similar normalised mean peak torque values for eccentric hamstring reported for both the control and the ACLR group at three months. Therefore, future research could consider changes meaningful if more than 0.30 $N.m.kg^{-1}$ for the eccentric hamstring to be meaningful and beyond measurement error.

SEM values for the normalised peak torque hamstring with the mode of concentric contraction for the control group (0.24 $N.m.kg^{-1}$) was lower than the ACLR group at three months (injured side= 0.43 $N.m.kg^{-1}$ and non-injured side=0.38 $N.m.kg^{-1}$). Also, the 95% CI was fair to good for the control group and poor to good for the ACLR at three months, suggesting there is real difference exist in performance between two groups. Even though the good ICCs>0.70 reported for the control group and fair ICCs for the ACLR group at three months. But the normalised mean peak torque values for concentric hamstring for both limbs in the ACLR group at three months were higher than the control group (Table 2). The ACLR group had a regular physiotherapy and rehabilitation session, two times a day and twelve sessions per week. Also, the ACLR group started isokinetic knee flexor and extensor five weeks after ACLR surgery to restore strength with the mode of isometric and progress to the mode of concentric and eccentric contraction for both hamstring and quadriceps after ten weeks following ACLR. But the control group did not have a regular isokinetic knee strength exercises with the complex protocol (concentric and eccentric quadriceps and hamstring) to become familiarise with the mode of contraction and gain strength before the isokinetic knee strength test. Also, the control group's body mass was lower than the ACLR group, which might be indicative of lower muscles mass due to the different types of sport and their training frequency and background, which could produce lower peak torque compared to the ACLR group (refer to chapter four for further details). Therefore, future research could consider changes greater than 0.45 $N.m.kg^{-1}$ for the concentric hamstring to be meaningful and beyond measurement error. Considering the SEM value for the eccentric contraction of quadriceps, the dominant side of the control group (0.56 $N.m.kg^{-1}$) was higher than the ACL group at three months (injured and non-injured side=0.21 $N.m.kg^{-1}$). Also, the 95% CI was good to excellent for the control group and poor to fair for the ACLR group at three months, suggesting that there is a real difference in performance with the mode of eccentric quadriceps. Despite the fact, the good to excellent ICCs reported for the control group, but the control showed poor normalised peak torque values along with large SEMs compared to the ACLR group at three months. Future research could, therefore, consider changes greater than 0.25 $N.m.kg^{-1}$ to be meaningful and beyond measurement error for eccentric quadriceps contraction.

The fair ICCs was established for QASLS during SLS and SLHD for the control group. Further, the fair to good ICCs was reported for the QASLS during SLS and poor to the fair during SLHD for the ACLR at three months (Table 4 and 5). Considering the SEM values for the QASLS, the mean absolute value for the dominant side of the control group (SLS= 0.45 and SLHD= 0.66) were higher than the ACLR group at three months during SLS (injured side=0.80 and non-injured side= 0.96) and similar to SLHD (injured side=0.63 and non-injured side= 0.37). Also, the 95% CI was identical for the control and ACLR group at three months. But the QASLS during SLS on the non-injured limb for the ACLR group was higher compared to the control group, suggesting that the ACLR at three months showed different ICCs and SEM between injured and non-injured limb during two tasks. Such findings represent differences in the magnitude of measurement variance (variability) within each limb (Denegar and Ball, 1993; Portney and Watkins, 2009). It appears that there can still be substantial differences in between-limb reliability and measurement precision for the ACLR group at three months during all tests in the current study. Therefore, future research could consider changes greater than 1 point to be meaningful and beyond measurement error in QASLS following ACLR at three months.

The good to excellent ICCs was established for all the subscales of KOOS and TSK for the control group. Further, poor to fair ICCs were reported for all the subscales of KOOS and TSK for the ACLR at three months (Table 4 and 5). Considering the SEM values for the KOOS and TSK, the mean absolute value of KOOS (symptoms= 10.37 and sport=16.42) for the ACLR group at three months were higher than KOOS (symptoms= 5.80 and sport=12.00) for the dominant side of the control group. Also, the 95% CI was higher for the control compared to the ACLR group at three months, suggesting that the ACLR at three months showed poor ICCs and SEM during KOOS and more fear of pain or reinjury compared to the control group. Therefore, the control group showed good to excellent ICCs with low SEM compared to the ACLR at three months.

There was no pain, swelling, and stiffness reported during all tests in the current study as a source of increased variability. The order of tests in the present study was designed from easy to hard tests to mitigate fatigue, and all participants instructed not to perform rehabilitation session for 48 hours before testing. Further, the same tester followed the same standardised measurement procedures for both limbs for all tests. The examiner consistently verbally encouraged all participants for all trials for both legs across all tests.

Comparison the relative and absolute reliability between the control group and the ACLR group at six months.

The good ICCs >0.70 was established for both the control and the ACLR group at six months during YBT, normalised peak torque eccentric quadriceps and concentric hamstring, QASLS during SLS, KOOS/sport and TSK (Table 4 and 5). Further, the good ICCs >0.70 was also established for 2D FPPA during SLS and SLHD for the ACLR group. Also, the good ICCs were reported for normalised peak torque eccentric hamstring, SLHD and KOOS (pain, symptoms, ADL and QOL) for the control group. Therefore, the YBT, normalised peak torque eccentric quadriceps and concentric hamstring, QASLS during SLS, KOOS/sport and TSK for the control and ACLR group can be used confidently in the clinical setting on different days. However, the SEM and 95% CI values were different between the ACLR group and the control group even though good ICCs reported for both groups. Although the SEM is the recommended convention for quantifying measurement precision, the SEM only represent 68% probability that the true score is within ±1 SEM of an observed score (Atkinson and Nevill, 1998; Portney and Watkins 1993). Therefore, the 95% CI is more rigorous and meaningful since it represents a 95% probability that a valid score is within ±1.96 SEM of an observed score (Batterham and George 2000). For instance, the SEM values for the control group and the ACLR group during YBT were similar ranged from 6.01-6.80 LL%. Still, the 95% CI were quite different between the control group

(0.96-0.99) and the ACLR group (0.53-0.97), suggesting that the control group showed better performance than the ACLR group based on the level of the 95% CI.

Future research could consider changes higher than 7cm to be meaningful and beyond measurement error for the ACLR group at six months for the YBT.

The fair ICCs were established for both the control and the ACLR group during isokinetic knee strength with the mode of concentric quadriceps. The SEM values for both groups were similar ranged from 0.31-0.38 N.m.kg^{-1}, and same 95% CIs were reported for both groups ranged from 0.22-0.84, suggesting that both groups performed poor performance in quadriceps strength. Regarding the normalised mean values between the control and the ACLR group at six months, the ACLR group showed better mean values ranged from 2.23-2.53 N.m.kg^{-1} than the control group 1.57-1.74 N.m.kg^{-1} (Table 2). However, the cutoff value in the current study did not meet the cutoff values >3.1 N.m.kg^{-1} by Pietrosimone et al. (2016) at six months following ACLR. Further, most athletes return to sports at six months following ACLR with quadriceps deficit, and the current study showed the poor level of 95% CI along with poor cutoff values. Therefore, the return to sport at six months should delay due to the poor relative reliability and poor cutoff value less than 3.1 N.m.kg^{-1} and the SEM value should greater than 0.40 N.m.kg^{-1} to be meaningful and beyond measurement error for concentric quadriceps.

The good ICCs for SLHD was established for the control group and fair ICCs for the ACLR at six months. The SEM values were lower for the ACLR group ranged from 21.16-22.10 LL% compared to the control group (26.80 LL%). Also, the 95% CI were different for both groups, suggesting that the control group showed a better level of the 95% CI compared to the ACLR group. However, the ACLR group at six months performed better in the normalised reach distance on both limbs during SLHD compared to the control group (Table 2). Also, the ACLR group at six months performed better mean values in quadriceps concentric and eccentric contractions compared to the control group (Table 4). But the quality of landing (2D FPPA) during SLHD was better in the control group despite the better quadriceps strength and power production for the ACLR group.

The ICCs for 2D FPPA during SLHD, the control group showed fair ICCs compared to excellent ICCs for the ACLR group at six months. Further, the SEM values were lower for the control group (1.8°) compared to the ACLR group (4.3°-4.4°). Still, the 95% CI were quite different between the control and ACLR group at six months, suggesting that there are real differences in performance exist between the two groups. The SEM values for 2D FPPA during SLHD should be higher than 5°, and the SEM values for SLHD should be higher than 23cm to be meaningful and beyond measurement error.

The fair ICCs was reported in QASLS during SLS and SLHD for both the control and the ACLR at six months. The SEM values during SLS and SLHD were similar for the control and the ACLR group. Also, the 95% CI were identical for both groups, suggesting that there were no real differences exist between the control and the ACLR group at six months. Future research could, therefore, consider changes more significant than 1 point to be meaningful and beyond measurement error.

The good ICCs were reported for the KOOS (pain, symptoms, ADL and QOL) and TSK for the control group. Further, the good ICCs were reported for KOOS/sport and TSK for the ACLR group. The SEM values for the KOOS (pain=7.52, symptoms=5.66, ADL=5.17 and sport=10.40) were lower for the ACLR group except for the QOL=16.99 compared to the control group. Also, the 95% CI was higher for the control group, suggesting that the control group performed better in the KOOS and TSK.

Comparison the relative and absolute reliability between the ACLR group at three and six months.

The good ICCs >0.70 was established for both the ACLR group at three and six months during YBT, 2D FPPA during SLS and SLHD and QASLS during SLS on the non-injured limb (Table 4). The SEM values for the ACLR group at six months were lower for the QASLS during SLS and 2D FPPA during SLS comparing to the ACLR group at three months. Also, the 95% CI were similar for both groups, suggesting that there were no real differences exist between the two tests. Therefore, one of the most important findings of the current study is that 2D FPPA and QASLS during SLS for the ACLR at six months can be used confidently in the clinical setting on different days.

The fair ICCs were reported for the ACLR group at six months during SLHD on both limbs. However, the good ICCs >0.70 were reported for the ACLR at three months on both legs. The SEM values were similar for both groups on the injured limb; also, the 95% CI were quite different for both group on the injured limb, suggesting that the injured limb at three months perform better compared to the injured limb of ACLR at six months. However, the consistency of the quality of landing (2D FPPA) during SLHD was improved from three to six months in terms of ICCs, SEM (Table 4) and mean values (Table 2). Therefore, the ACLR group at six months performed more consistently in controlling knee valgus with higher ICCs and lower SEM, suggesting that the higher ICCs for the ACLR group at three months during SLHD was due to possible compensation pattern from the upper chain (arm, trunk and hip) and larger SEM values during 2D FPPA (Table 4).

The ICCs for the normalised peak torque quadriceps eccentric and concentric hamstring improved from three to six months following ACLR (Table 4). The SEM values for the normalised peak torque quadriceps eccentric were higher for six months, but the SEM values for the normalised hamstring concentric were similar. But the 95% CI were quite different between three and six months, suggesting that the ACLR group at six months showed higher ICCs compared to the three months and so more consistent performance. Regarding the normalised mean values, the SD values were higher during eccentric quadriceps contraction ranged from 0.48-0.53 at six months compared to three months ranged from 0.24-0.44. Further, the SD values were similar during hamstring concentric contraction for the ACLR groups, but the normalised peak torque values were better at three months to compare to six months following the ACLR group. Therefore, the normalised peak torque mean values for concentric hamstring contraction were correct at three months because of the same SEM and SD values. In contrast, the normalised peak torque values for eccentric quadriceps contraction were not accurate at six months due to higher values of the SEM and SD compared to the ACLR group at three months. It seems that in the current study, there is no correlation between the good ICCs >0.70 and higher mean values during SLHD and isokinetic knee strength test. Perhaps future research should examine the relationship between ICCs and normalised mean values in the ACLR group because it allows clinicians to differentiate the good ICCs and the cutoff values when the athlete wants to return to play. Even though the current study assumed that the fear (TSK) was one of the reasons why the subject did not meet the cutoff value > 3.1 $N.m.kg^{-1}$ for the isokinetic knee strength test for the ACLR group, but the ICC for the TSK was improved from poor to good at six months. Further, the SEM and the 95% CI values were same for both groups, suggesting that there were no real differences exist in cutoff values from three to six months even did not meet the cutoff values greater than 4 points (Woby et al. 2005). Therefore, in the current study, the ACLR at six months did not improve fear and the KOOS (sport and QOL) from three months post ACLR.

Strength of this study is that this is the first study to establish relative and absolute reliability and on a male patient following ACLR at three and six months from the Middle East region. Furthermore, this is the first study to combine subjective questionnaires (KOOS, TSK) alongside quantitative measurement by SLS, YBT, SLHD, isokinetic knee strength with a unique mode of muscle contractions and finally assessed the quality of movements by 2D FPPA during SLS and SLHD merged with QASLS.

There are potential limitations to this study which include that the findings might not apply to the professional athlete's level either male or female. Also, the result of the present study might not apply to general populations either in male or female, as the present study was performed in male recreational patients from the Middle East region. Another limitation of the current study is that the rehabilitation program was not controlled for a group of patients with mixed sports for six months following ACLR. Therefore, it can conclude that the individual patient could have a different ACLR rehabilitation program which it could have either positive or negative effect on their rehabilitation progression to meet an acceptable cutoff value at three and six months following ACLR.

Conclusion

A similar level of consistency (high ICCs and low SEM values) was achieved during YBT and 2D FPPA during SLHD in the ACLR patients and control group. The control group was more consistent for a number of tests in this study, including SLHD, isokinetic knee strength, KOOS, and TSK compared to the ACLR patients. Worse performances (greater inconsistency) were seen in the isokinetic knee strength test, QASLS during SLS, SLHD, KOOS, and TSK for the ACLR patients at three months ICCs and SEM values. The consistency of the isokinetic knee strength performance, QASLS during SLHD, and TSK improved from three to six months on the ACLR patients. When making decisions over progressing ACLR patients or RTS, clinicians should therefore consider this inconsistency of performance and the level of measurement error in the tests. Also, it might change over time to make the most reasoned decision about whether they see an actual performance or a meaningful change in performance.

An important finding of the current study was the deficit in eccentric quadriceps at six months following ACLR with 26% passed the normalised peak torque value >3.1N.m.kg^{-1}, which is a poor outcome with regards to the recovery of quadriceps and may have influenced the performance of a number of the other tests previously discussed. Though clinicians must take into account that even with good to excellent relative and absolute reliability in typical performance tests, the quality of performance and ongoing rehabilitation would appear to be critical factors to return the patients to reasonable levels of function. The findings of this study should provide clinicians with a guide to what are potentially meaningful changes across a large number of tests used to measure outcome from ACLR, this should aid decision making with regard to patient progression. This is finding though influenced to an extent by the inconsistency of performance between testing sessions, would even when taking into account measurement error still be poor and under the cut off value for the majority of patients, therefore it cannot be concluded that measurement insensitivity alone is creating this poor outcome.

The fear of pain/ re-injury (TSK) and KOOS (sport and QOL) did not improve from three to six month following ACLR, this again is likely to influence performance of a multitude of tests and may have been influenced by the consistency of performance of these tests. How fear influences consistency of test performance and ability to achieve best scores, is something which requires further investigation.

Chapter 6

Discussion

The overarching aim of this thesis is to improve the understanding as to why the outcomes from ACLR are poor. In order to achieve these nine individual objectives were covered. The first objective of this thesis was to discover which if any study/studies utilised multiple domains of measurement to describe outcome in ACLD patients and patients following ACLR at three and six months. The use of single or limited numbers of outcome measures to evaluate performance would mean a full picture of performance is missing. As has been discussed ACL injury, graft rupture and development of other significant comorbidities is likely to be related to the occurrence and interaction of multiple factors. Therefore, the absence of critical evidence from these multiple sources could have a substantial impact on the ability to decision making effectively regarding both risk and patient progression. The finding of the literature review within chapter 2 revealed that no single study had used a significantly large combination of different tools. Therefore, it is imperative for the clinicians and practitioners to utilise multiple tests after ACL injury and following ACLR in future studies to gain a better multi-dimensional understanding of the patient's performance.

One of the most interesting secondary findings of the literature review (chapter 2) was that no study had performed any form of quality of movement assessment during dynamic tasks for the ACLD group and ACLR at three and six months postoperatively. Most papers focused on the quantity of the movement rather than focusing on the whole-body movement quality during unilateral landing, as one of the primary risk factors during ACL injury is knee valgus and trunk displacement this could be an important omission in understanding performance.

The second objective of the study, which was also covered in chapter 2 was to discover if any previous studies had reported relative and absolute reliability for a variety of outcome measures in ACLR patients at three- and six-months post-operation. The findings of chapter 2 revealed that no study examined relative and absolute reliability for the tests undertaken in ACLR patients at three and six months. For a practitioner to confidently perform and be able to extract true meaning of the results of all the above tests, the relative and absolute reliability must be known. Lack of reliability and measurement precision data could undermine the validity of raw data and compromise data analysis procedures and practitioners' decision-making (Batterham & George, 2003; Clark et al., 2016). This then becomes clinically relevant when trying to understand if sufficient progress is being made, if the level of measurement error has not been identified, the clinician cannot understand if a meaningful (above measurement error) change has occurred. The absence of data on meaningful change could leave clinicians assuming progress has been made when in fact the changes seen could be purely due to chance, as they sit within the measurement error of the tool used.

The third objective of this thesis was to compare the results of multiple tests between ACLD patients who were candidate's for ACLR surgery and a control group. Specifically, to compare an ACL injured limb to non-injured limb, an ACL injured limb to control limb and non-injured limb to control leg to understand if any deficits were present prior to surgery, as pre-operatively deficits have been linked to post-operative outcomes. This is particularly important in relation to quadriceps strength (concentric and eccentric contractions) as traditionally, after ACL injuries, the non-injured limb would be used as a reference limb for comparison after ACLR surgery to calculate limb symmetry index. There is a risk that atrophy occurs during rehabilitation (of the non-injured limb), so understanding and establishing baseline values becomes critical, as, after ACL injury, the non-injured limb was shown to have a 25.5% quadriceps deficit after 23 days (Hannon et al. 2017). Therefore, utilising non-injured limb as a reference limb for side-to-side comparison should only be undertaken after careful consideration after an ACL injury to predict and assess the outcome measures following ACLR at three and six months. Lack of awareness of the potential for a detraining effect on the uninjured limb in ACL patients could then lead to an over estimation of performance, which again is likely to have an impact on the efficacy of decision-making regarding patient progression.

The limb symmetry indices are calculated between the involved and uninvolved limb for strength testing, a battery of hop tests, quality of unilateral movement (SLS) and landing task (SLHD) during to determine readiness to return (Hannon et al. 2017). The finding of chapter 3 demonstrated that the control group showed better scores in all tests except for isokinetic strength testing. This potentially indicated a few things:

- The patients may have had performance deficits which predisposed them to injury.

- Performance across a variety of tests could decrease rapidly following ACL injury.
- Familiarisation with and training on isokinetic equipment improves strength in ACLD patients (the potential reason for difference with controls). This learning effect may need to be accounted for in future studies because again it could be a source of over estimation of performance.

The decreases in performance between the injured and non-injured limb appear to be test specific, which would need considering when planning rehabilitation and progression decision making. Quality of movement and strength differed between tested limbs. But the ACLD and control group showed symmetrical performance in the YBT, 2D FPPA for SLS and SLHD tasks, normalised hamstring peak torque for concentric contractions. It would appear that performing pre-operative rehabilitation could be recommended to strengthen the quadriceps along with restoring full knee range of motion and reduce the fear and quality of movement during single-leg tasks starting from low load/impact with proper full-body movement alignment to improve the confidence of athletes for faster recovery and RTS. A further consideration is that using the LSI may underestimate performance deficits. Further, it should be calculated either from baseline (pre-injury or as close to injury as possible to injury) data from the contralateral non-injury limb to discover true performances for each task as a criterion for RTS after ACLR.

The fourth objective of this thesis was to report outcomes from a battery of tests at three and six months following ACLR surgery (chapter 4) in a previously unreported upon male population. Regarding the timeline at three months following ACLR, this is the first study which examined multiple tests following ACLR surgery. This is important because at three months the most professional athletes following ACLR start to add running into their rehabilitation programmes, this change in loading increases risk of re-injury and joint stress and without appropriate information the decision to progress becomes an unsupported one. One of the rationales for not using isokinetic knee strength test and SLHD at three months following ACLR were due to them potentially placing high loads on the ACL graft. However, as mentioned in chapter 4, no clinical symptoms were identified during multiple tests at three and six months following ACLR postoperatively, so from a tissue stress perspective the tests would appear appropriate. Therefore, the sports physiotherapist could use the current study's multiple tests with confidence once monitoring the clinical symptoms along with new cut-off values for each test at three months following ACLR. The findings in chapter 4 demonstrated that the quality of landing during SLS and SLHD was poor compared to the control group, suggesting that it is insufficient to merely look at the quantitative data (distance) without also considering the way the patient is performing the task. However, straight-line activities such as running may be acceptably performed neuromuscular rehabilitation exercise to improve movement quality would be recommended before introducing more demanding load such as change of direction and plyometric drills. This also emphasises the need to assess both the quantity and quality of movement to inform decision making regarding exercise progression.

The fifth objective of this study was to examine the performance during multiple tests between the ACLR group at six months and the control group. The findings in chapter 4 demonstrated that the control limb was still superior in YBT, 2D FPPA during SLS and SLHD and all subscales of KOOS than both limbs of the ACLR group at six months. So, the rehabilitation to that point had failed to address all performance deficits. This so how the importance of assessing the patient across multiple measurement domains, to give a holistic picture of the level of deficits and should have a positive impact on any return to training decisions which would have to start to be made at this stage.

The sixth objective of this study was to examine the multiple tests between injured limbs for the ACLR group at three and six months to assess which areas progress over the period. The findings in chapter 4 demonstrated that the ACLR injured limb at three months show better scores in the SLHD and normalised peak torque quadriceps concentric contraction and eccentric contraction of the hamstring muscle. This might indicate that the emphasis in the early rehabilitation phase was successful at improving strength and force generation (SLHD), which was not maintained as the possible emphasis of rehabilitation shift to concentrating more on movement quality. This then emphasises the need to maintain all aspects of performance throughout the rehabilitation period and perhaps not switch focus too much, at the expense of one element.

Generally, the outcome relating to quadriceps strength was poor, with only 26% of patients at six months achieving the relative peak torque value >3.1N.m.kg^{-1}. As poor quadriceps strength has been linked to poor long-term outcomes and OA development, this is an area which would need addressing, and also understanding why the rehabilitation programme used failed to recondition the quadriceps. This finding is not unique to this study, it is a finding consistent across the majority, it perhaps shows a failing of current rehabilitation approaches to manage and improve this important aspect.

The most novel objective of this thesis was to establish the relative reliability and absolute reliability for the KOOS, TSK, YBT, isokinetic knee strength test, 2D FPPA during SLS and SLHD and QASLS during SLS and SLHD for the ACLR patients at both three- and six-months and controls (objective 7,8, and 9). The control group was more reliable across several tests when compared to the 3-month ACLR data, this would indicate using reliability data from a control group is not always appropriate when looking at the performance of ACLR patients at three months post-operation. Therefore, when clinicians making decisions over progressing ACLR patients at three months to for example return to running they should consider this inconsistency of performance and the level of measurement error in tests, to make the most reasoned decision, this needs to be based on specific scores from this patient group ideally.

The findings of chapter 5 demonstrated that the consistency of performance of the isokinetic knee strength, QASLS during SLHD tests improved from three to six months on the ACLR patients. Some other tests had similar levels of reliability (TSK and KOOS (sport and QOL)) at both three to six months following ACLR. Why the consistency of performance of some of these tests improved was not studied, it may have been related to improving confidence (TSK improved over time). How fear affects the consistency of test performance and ability to achieve the best scores, is something which requires further investigation. These findings have implications for clinicians undertaking ACLR rehabilitation, having an accurate understanding of measurement error gives greater clarity of what is a meaningful change in a measure. Some of the current issues with a precise prediction of outcome from ACLR may be related to the lack of sensitivity of measures being used to support the decision-making process, data from this study may help improve this understanding.

Conclusion

When considering the overall findings and comparing the ACLR group at three and six months, the ACLR group improved from three to six months postoperatively in the YBT, 2D FPPA and QASLS during SLS and SLHD, all the KOOS subscales and TSK, showing the positive benefits of continued rehabilitation. Also, the potential for these measures to be sensitive to change as the patient's performance improves across multiple domains occurred (the improved consistency of test performance) improving potential confidence in decisions made based on this data. The strength of the quadriceps (reduction of deficit) improved from three to six months, but even at 6 months very few patients passed the >3.1 $N.m.kg^{-1}$ criteria. These findings are consistent with those in the literature reported in chapter 2, with ACLR patients improving across a number of functional tests but still have significant deficits in quadriceps strength. This ongoing deficit in quadriceps strength has the potential to increase the risk and further ACL injury and osteoarthritis in the knee, along with decreased long-term function as discussed in chapter 2. It would appear the rehabilitation undertaken by patients in this study was sufficient to improve function but ineffective at improving quadriceps strength, future study is required to identify the best means of improving quadriceps strength, whilst also improving function.

All of the outcomes above were taken on face value, with often reported significant improvements, but without understanding the level of measurement error in those tests, it cannot be truly understood if the changes were clinically meaningful, that is of a greater magnitude than measurement error. The majority of the tests undertaken showed good to excellent relative reliability and small margins of absolute measurement error (SEM). Isokinetic strength testing showed some of the poorest scores for absolute and relative reliability, this could significantly impact on understanding the level of deficit in strength these patients have shown. It also makes it difficult to confidently progress the patient if one of the progression criteria is based on a critical level of strength. This was especially true a 3-month post operation testing, with reliability improving at the 6-month test. As discussed in chapter 2 the ability to generate sufficiently high levels of force early in rehabilitation has been linked to better outcomes, so understanding why patients are unreliable at testing would be an important future direction for study. The poor reliability of the isokinetic knee strength for the ACLR group at three months could be related to the complexity and mode of muscle contraction at the early rehabilitation stage. Therefore, one of the possible alternative methods for future study would be to use the more straightforward muscle contraction mode, such as concentric or isometric contractions for the quadriceps and hamstring muscles, to improve the reliability. Further, muscle inhibition or fear of injury (TSK scores) were significantly lower at this stage, but without consistent measurement it will be difficult to investigate these aspects accurately.

Recommendation for future research

This study only presented relative and absolute reliability scores for a male middle eastern ACLR population these scores may differ with gender, ethic group, age and sporting background, but this data still at least provides a clinician with some data from which to start to base their clinical judgements which was not previously available. Current practice would appear not to account often for judging changes in performance against measurement error for any particular test, this obviously could decrease the validity of the result and so impact on the strength of clinical decision making. By starting the process of providing data on improving understanding of meaningful change, this might help decision making in ACLR patients regarding both progression in rehabilitation and RTS.

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