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Strength profiling using isokinetic dynamometry following anterior cruciate ligament (ACL) reconstruction:

Implications for rehabilitation and return to sport decision making.

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i Declaration Sheet

I declare that the work in this thesis was carried out in accordance with the regulations of the University of Gloucestershire and is original except were indicated by specific reference in the text. No part of the thesis has been submitted as part of any other academic award. The thesis has not been presented to any other education institution in the United Kingdom or overseas. Any views expressed in the thesis are those of the author and in no way represent those of the University.

Adrian James Hammond

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ii Acknowledgements

I embarked on this studentship at the university of Gloucestershire in collaboration with Aspetar Orthopaedic and Sports Medicine hospital, Qatar, to complete this thesis with an idea of helping to improve the isokinetic testing protocols at the late stage of returning to sport (RTS) after anterior cruciate ligament reconstruction (ACLR) in professional Qatari male athletes. Initially, the idea was vague, and ranged in multiple directions we could have taken this work and required a strategic framework that would allow me to achieve my aims. Prof. Mark De Ste Croix, Dr Jonathan Hughes and Dr Paul Read have provided an environment and guidance for which I could develop the framework for the thesis. All three supervisors have been sources of inspiration, direction, and support through the duration of this thesis and for that I thank you unreservedly, without this, the thesis may still have not been written. Until I started this degree, I had never met Mark, Jon, or Paul before my enrolment, but their generosity with their time, openness and honesty in discussion has meant that I now consider them all as mentors and friends. I would like to further extend this thank you to Mark who took the time to fly out to Qatar with me for five days in May 2019 to undertake a site visit to Aspetar our collaborating partner. A further thank you to Paul, who welcomed us to Qatar and organised our stay at Aspetar. It was a pleasure to have this opportunity to fly out and see how sports science is conducted in such a prestigious setting. I would like to personally thank Paul and his family for his generosity in hosting us for a BBQ and taking time to show us some of the sights in Qatar including three hospitals. Thank you all for making this process informative and for your continued support. I know it probably has not been the easiest of supervisions. I have doubted myself more often than most but thanks to you all I have managed to overcome this challenge when at times I thought this was unachievable.

This thesis hopes to build on the work of some excellent researchers from across the Sport and Exercise Science field in isokinetic testing and RTS criteria after ACLR. The research would not have been possible without willing participants and the collaboration of Aspetar. I would like to thank Aspetar and all the athletes who were willing for their data to be used in this retrospective study. I hope that the research process, discussions, and findings have contributed to highlighting the need for strength profiling when using isokinetic testing to safely return athletes back to sport post ACLR.

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iii Abstract

The evaluation of isokinetic muscle strength testing using peak torque (PT) values to identify muscle strength deficits in quadriceps and hamstrings following anterior cruciate ligament reconstruction (ACLR) at the point of return to sport (RTS) is one of the most used tests for discharge criteria. It has readily been used in previous literature to identify if athletes meet limb symmetry of the uninvolved leg following ACLR at the time of RTS. However, studies have found that the use of a single PT value lacks the reliability to highlight residual strength deficits across the full range of motion (RoM), leading to an overestimate of muscle strength function. Research has suggested that torque-angle analysis should be conducted over a full RoM to further identify residual knee extensor and flexor muscle strength deficits at the point of RTS.

The aim of this thesis was to examine isokinetic strength in soccer players and other pivoting athletes using the traditional methods including PT and limb symmetry index (LSI) thresholds in addition to a strength profile which considers torque production across the full RoM tested. The use of strength profiling is proposed to provide a greater depth of analysis which may have potential implications for RTS decision-making, and subsequently, late-stage rehabilitation.

The study hypothesized that athletes who 'pass' the traditional RTS test protocol of ≥ 90% quadriceps PT LSI will still display residual deficits when the torque-angle curve is examined. Data was collected retrospectively from twenty-five Qatari male athletes who had undergone primary ACLR and played level 1 professional sport in Qatar. With inclusion criteria ensuring all athletes had to achieve ≥ 90% quadriceps PT LSI across repetitions 2,3 and 4. Isokinetic strength assessment for quadriceps (concentric) and hamstrings (concentric and eccentric) were performed on both the involved and uninvolved limbs at 60˚/s (Biodex). Average torque values across each six 10˚ window (20˚-29˚, 30˚-39˚, 40˚-49˚, 50˚-59˚, 60˚-69˚ and 70˚-79˚) were used to form an LSI % to inform of potential strength deficits. Hamstring to Quadriceps (H:Q) ratios were also conducted across all the torque-angle windows using an average torque and compared against the traditional methods.

The results for LSI of average torque across the six 10˚ windows on all testing protocols show that only 28% (7/25) participants achieved a ≥ 90% mean torque LSI across all six 10˚ segments at all three testing protocols. Therefore, 72% (18/25) who were deemed safe to RTS based on a ≥ 90% quadriceps PT LSI showed residual deficits in at least one 10˚ window of knee flexion when assessing residual deficits in knee extension and flexion muscle strength. The study also highlights of those that have had a hamstring (HS) graft only 8% achieved ≥ 90%

LSI across all 10˚ segments at all three testing protocols compared with 46% (6/13) who achieved this after having bone-patellar tendon-bone (BPTB) graft. Only one significant main effect was found in the 10˚ segment variable found in all three measures: Hamstring concentric $F (1.76, 115) = 51.47$, $P < .001$, $r = 0.83$, Hamstring eccentric $F (1.46, 33.65) = 67.11$ $P < .001$, $r = 0.57$ and Quadriceps concentric $F (5, 115) = 173.51$ $P < .001$, $r = 0.63$.

This study highlights further research needs to be conducted into the use of torque-angle analysis across a full RoM using average torque values, as opposed to the sole use of a PT value for identifying 'safe' RTS after ACLR.

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List of Abbreviations

The following abbreviations have been defined in text in the first instance:

Abbreviation	Definition	Unit
ACL	Anterior Cruciate Ligament	
ACLR	Anterior Cruciate Ligament Reconstruction	
ATT	Anterior Tibial Translation	
AE	Athlete Exposures	
BPTB	Bone-patellar Tendon-Bone Graft	
Cm	Height	Cm
CoD	Change of Direction	
CON	Concentric	
ECC	Eccentric	
EMG	Electromyography	
H:Q	Hamstring to Quadricep ratio	
HS	Hamstring Graft	
IKD	Isokinetic Dynamometer	
IR	Incident Rates	
LSI	Limb Symmetry Index	LSI %
M	Body Mass	kG
MOI	Mechanism of Injury	
Nm	Newton meters	nM:kG
PT	Peak Torque	
RFD	Rate of Force Development	
RoM	Range of Movement	
RTS	Return to Sport	
SLHD	Single Leg Hop for Distance	
SKLR	Swedish Knee Ligament Registry	
TLHD	Triple Leg Hop for Distance	

Chapter 1 Introduction

1.1 Research Overview

Anterior cruciate ligament (ACL) injury is traumatic and can result in substantial time-loss from sport/physical activity. There is also an increased risk of osteoarthritis, degenerative knee cartilage conditions, and athletes being unable to attain previous levels of sporting activity (Ardern et al., 2016; Neuman et al., 2008). ACL reconstruction (ACLR) is often recommended especially if an athlete is looking to return to pivoting and cutting sports (Hewett, Myer & Ford, 2006; Marx et al., 2003). However, athletes do have the option to go through a conservative non-surgical route which involves a strict and rigorous rehabilitation plan which can be suffice (Rodriguez et al., 2021). The two routes are often determined by the functionality of the knee and the athletes long term goals, generally, athletes who have repeated instability require ACLR to restore knee stability and enhance neuromuscular control. A report published by the Swedish Knee Ligament Registry (SKLR) suggests that 80/100,000 people have ACL injury meaning around 8,000 individuals suffer ACL injuries with approximately 4,000 undergoing surgery per year (Swedish Knee Ligament Registry, 2020). Whilst research offers positives and negatives to both a surgical and non-surgical option, a pragmatic approach needs to be taken during the decision-making process considering the athletes knee function requirements and timescales post initial ACL injury (Buerba et al., 2021; Rodriguez et al., 2021). In Sweden, soccer was the most common activity that contributed to ACL injury, in 2020 soccer was the cause for 29% and 49% of ACL injuries in female and males respectively (Swedish Knee Ligament Registry, 2020; Persson et al., 2022). This registry data has been collected over a 15-year period in Scandinavia and while this cannot necessarily be attributed globally to how many primary and secondary ACLR's occur, it does allow for a comparison with non-surgical treatment. It represents that at least 50% of patients require surgery especially when wanting to return to high level elite sport (Persson et al., 2022). Evidence from the SKLR does not distinguish the level of sport they played at or returned too, so this needs to be considered when comparing with other countries. However, the benefit is the data has been collected longitudinally and therefore, presents a wealth of insightful information which contributes towards the decision-making of a conservative non-surgical approach or surgical treatment approach after ACL injury.

Athletes who therefore undergo ACLR are usually cleared to return to sport (RTS) between 6-12 months post-surgery (Barber-Westin & Noyes, 2011; Harris & Abrams et al., 2014). Grindem et al (2016), reported that athletes who return earlier than nine months post-surgery are at an increased risk of re-injury, and this is compounded when there are deficits in physical function. Specifically, reduced quadriceps and hamstring strength are frequently observed in both the involved and uninvolved limbs and indicate incomplete functional recovery after

ACLR. Persson et al (2022) observed a greater proportion of patients who underwent ACLR reported higher quality of life and knee function than those treated non-surgically in a cross-sectional 10-year follow-up. However, it should be noted that literature is sparse and outcomes after non-surgical treatment is limited thus comparatively lacks evidence to challenge the factors that affect athletes who undergo ACLR. Further research is warranted to assess the strength deficiencies in non-surgically treated athletes to ascertain if similar strength deficits are present to those who undergo ACLR.

Research has consistently identified that at the time of RTS, athletes display decreased levels of muscular strength compared to pre-injury levels and the contralateral limb at the time of RTS (Benjaminse, Holden, & Myer, 2018; Wellsandt et al., 2017). It is well documented that the most common muscular strength assessment is via the use of an isokinetic dynamometer (IKD) to establish knee extensor and flexor torque production (Undheim et al., 2015). This test forms one aspect of the RTS testing battery with peak torque (PT) which is the main variable reported and utilised for clearing athletes to RTS. While providing some indication of an individual's strength capacity, PT only represents a single data point across the torque-angle profile. Using this approach, a strength profile across the range of motion (RoM) cannot be determined and deficiencies in knee function may not be identified, thus returning an athlete to their sport inadequately. PT values are also assessed against the uninvolved limb, using a limb symmetry index (LSI), with a cut-off of 90% considered acceptable to meet 'pass criteria' (Abrams et al., 2014). Symmetry in muscle strength across the full RoM will therefore not be examined in athletes. This could ultimately withhold vital information which could affect RTS decision-making protocols for clinicians. There is a need to identify and characterise, if strength deficits are present at the end stage of rehabilitation to mitigate risk of secondary or contralateral ACL injury (Ardern et al., 2014; Grindem et al., 2016). Most importantly assessment of muscle strength across the tested RoM can be used to identify angle-specific windows which accurately depict where deficits are occurring.

In addition to the measurement of PT and limb symmetry, the hamstring to quadriceps (H:Q) ratio is also examined in literature to present an understanding of the key muscle synergists that cross the knee joint (Dvir et al., 1989). H:Q muscle ratio has been used to detect and identify muscular imbalances, knee joint stability and function while also being used as an indicator for lower body injury prevention and rehabilitation strategies (Aagaard et al., 1998; Coombs & Garbutt., 2002; Ruas et al., 2019). Hamstrings and quadriceps play a key role in knee stabilization, there is a reliance on these muscles to increase joint stability, joint contact forces and to reduce and counteract the anterior shearing load on the ACL from the tibia relative to the femur (Aagaard et al., 2000; Huang et al., 2017; Kellis & Baltzopoulos., 1997; Osternig, 2000). The role of the gastrocnemius should also be identified in relation to the hamstrings and quadriceps. Both the medial and lateral gastrocnemius heads attach across the knee joint and act as an antagonist to the ACL (Adouni, Shirazi-Adl & Maroune, 2015). The gastrocnemius and soleus are primary muscles of the leg offering major stability to the ankle and knee joints (Boden et al., 2010), whilst resisting external moments it helps to control and absorb forces to the knee and therefore trying to unload the ACL of any contractile forces. When the gastrocnemius activity is simulated, it is understood that the strain on the anteromedial bundle of the ACL is lower at all knee flexion angles compared to when the gastrocnemius and quadriceps are simultaneously active and producing high forces on the ACL over the entire knee flexion range (O'Connor, 1993; Durselen et al., 1995). Understanding the role of the gastrocnemius in stabilization to the knee and ACL allows research to continue to identify how it plays a protective role in reducing ACL force during single leg landing and take-off manoeuvres (Alerton-Geli et al., 2015; Ali et al.,2014). Morgan, Donnelly and Reinbolt (2014) reinforce that elevated gastrocnemius forces could function to replace or work in conjunction with the hamstrings to mitigate the risk of ACL injury during dynamic movements in sport. Moreover the coactivation of the hamstrings and quadricep muscle groups is necessary for movement efficiency and joint stability during active knee extension (Kellis & Katis, 2007). It should be then considered that due to the force-length relationship, PT of the hamstrings and quadriceps occur at different joint angles, and thus is not representative of dynamic knee joint stabilization. Therefore, measurement of H:Q ratio at corresponding joint angles is required to characterise agonist/antagonist function more accurately. The functional ratio (FR) (Hamstring eccentric/Quadriceps concentric) offers a differential to the conventional H:Q ratio. Ruas et al, (2019) found that conventional ratio does not consider other neuromuscular variables that can impact the agonist and antagonist muscle relationship such as torque produced at multiple angles, muscle size or muscle fatigue. Subsequently, it was hypothesized that alternate methods of H:Q ratios such as FR demonstrated greater functionally relevant to neuromuscular mechanisms that underpin strength between the quadriceps and hamstrings that can attributed to sport performance (Ruas et al., 2019). Aagaard et al, (1998) suggested that the use of FR around 1.0 offered appropriate balance on H:Q ratios, but they did find that lower hamstring eccentric strength reduced the protective element to the ACL. Consequently, a reduction in hamstring strength especially eccentric strength at an extended knee joint position can increase risk of injury (Cohen et al., 2014; Delextrat et al., 2020). There is limited research which has examined alternative H:Q ratios using a torque-angle approach in soccer players at the time of RTS from ACLR, this needs to be investigated in future research to help understand if using alternative methods such as a FR at angle-specific windows provides greater indication of when an athlete is ready to RTS and progress through rehabilitation.

Cumulatively, it can therefore be suggested that further research is required to assess knee strength using a more comprehensive approach in athletes who wish to RTS after ACLR. Moreover, a PT value only highlights a singular point in time during the toque-angle curve or at a specified angle. It is prudent, then, to identify that if an average torque value used over specific torque-angle windows can elicit a more comprehensive output of knee function than just a PT value alone. This would potentially look to align with research conducted by Eitzen and Shultz (2010) who suggest that their largest quadriceps strength deficits occur at knee flexion angles of ≤40˚ and that PT values did not identify the greatest strength deficits. Therefore, the aim of this thesis is to examine isokinetic strength in soccer players and other pivoting athletes using the traditional methods including PT and LSI thresholds in addition to a strength profile which considers torque production across the full RoM tested. The use of strength profiling is proposed to provide a greater depth of analysis which may have potential implications for RTS decision-making, and subsequently, late-stage rehabilitation.

1.2 Thesis specific aims:

1. To provide an overarching description of the angle of PT, H:Q ratios and LSI at six 10˚ torque-angle windows using an average torque on isokinetic movement of the hamstring and quadriceps. To determine strength profiling for ACLR athletes at concentric and eccentric contractions at 60˚/s at the point of RTS.
2. To investigate if those athletes that 'pass' their RTS assessment using a traditional approach of PT and LSI threshold > 90% value, display residual deficits of muscle strength when a more comprehensive strength profile including assessment of the entire torque-angle window is included, when using an average torque value at six interspersed 10˚ segments rather than PT.
3. To provide a H:Q conventional and functional ratios using a PT value. To provide H:Q conventional and functional ratios for each of the six 10˚ toque-angle windows using average torque values as a comparison to just a H:Q ratio PT.

1.3 Thesis Hypothesis

The hypothesis is that athletes who 'pass' the traditional RTS test protocol of ≥90 % quadriceps PT LSI will still display residual deficits when the torque-angle curve is examined. Hamstring and quadricep muscles at six specified 10˚ torque-angle windows of knee flexion (20˚-29˚, 30˚-39˚, 40˚-49˚, 50˚-59˚, 60˚-69˚ and 70˚-79˚) will highlight that PT values are a misleading value for 'passing' RTS criteria compared with a comprehensive strength profiling. These data can identify deficits which would have implications on decision making for the safe RTS of an athlete and would provide data which could determine the progression of rehabilitation after ACLR.

Chapter 2 Literature Review

2.1 Anatomy of the ACL and the Effects on Neuromuscular Function

The main role of the ACL is to prevent anterior shear of the tibia on the femur, with a secondary function of controlling knee rotation (Palastanga & Soames, 2012). The ACL is constructed of the anteromedial and posterolateral bundles. When the knee is in flexion the anteromedial bundle is taut and when the knee is in extension the posterolateral bundle is taut. The ACL is always under contractile tension in all knee flexion angles which results in the ACL restricting rotation of the knee and anterior translation of the tibia in relation to the femur in most knee flexion angles (Marieswaran et al., 2016). Contractile tension is defined as the ability to which the ACL contracts (change in length with respect to original length) to absorb strain from the forces put through the ligament via the agonist and antagonist muscles surrounding the knee during movements (Escamilla et al., 2012). The forces acting on the ACL under various flexion angles are present in combinational loading such as anterior force, internal/external torque, and valgus/varus motion (Marieswaran et al., 2016). The hamstrings (knee flexors) and quadriceps (knee extensors) play a crucial role in knee joint stability and there is a reliance on these muscles to increase joint contact forces and reduce shearing load. The capacity of hamstrings and quadriceps to produce relevant force to balance the antagonists whilst co-contracting is vital for knee joint stability and the reduction of ACL incidence (Osternig, 2000). Studies have found that in the majority of ACLR patients, strength deficits are regained over ~5 years following ACL injury (Palmieri-Smith, Thomas and Wojitys., 2008). However, Ageberg, Patterson and Friden, (2007); Fink et al., (2001); Risberg et al., (2016) and Tengmen et al., (2014) suggest that deficits ranging from 3.5%-12% can be found in quadriceps strength more than 10 years later in patients.

Whilst the ACL is a knee joint stabiliser, it should be noted that 2.5% of the genetic make-up of the ACL consists of mechanoreceptors. These are greater at the femoral and tibial ends of the ligament which has been examined via initial morphological analyses (Zimny, Schutte & Dabezies, 1986). Mechanoreceptors have a direct link to neuromuscular control of the knee. Changes in these structures, and neural patterns such as acceleration, deceleration, movement and more critically knee position results in altered spinal and supraspinal motor control (Young et al., 2016). Meaning that if mechanoreceptors are deficient within the ACL, a change in recruitment and movement patterns, proprioception and postural control will be compromised, causing serious alterations in neuromuscular function (Barber-Westin & Noyes, 2011). As a consequence, biomechanical factors such as varus deformities and valgus positioning when landing from jumping movements or change of direction (CoD) stress the knee, increasing the contractile tension (King et al., 2021; Zlotnicki et al., 2016). This relationship therefore proves the necessity of outlining strength deficits in the involved and uninvolved limbs after ACLR. Therefore, neuromuscular inhibition of hamstring and quadriceps should be closely monitored as it may promote a reduction in knee extension and flexion strength contributing to an increase in injury risk. Positions where the knee is close to full extension or minimal knee flexion angles 20˚ - 40˚ (figures 1 and 2 represent these positions in a seated view but also in the mechanism by which ACL injury occurs) will have residual deficits in strength if mechanoreceptors are inhibited (Arnold et al., 2009).

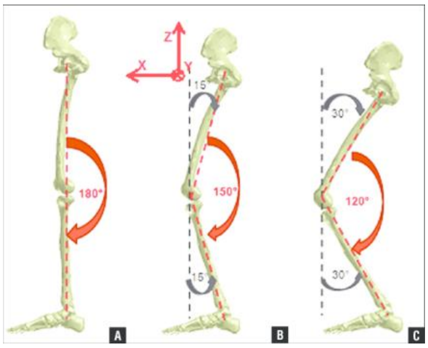

Figure 1. Shows full hip extension 180˚, 150˚. & 120˚ along with knee flexion of 15˚& 30˚ (Hinckel, 2016).

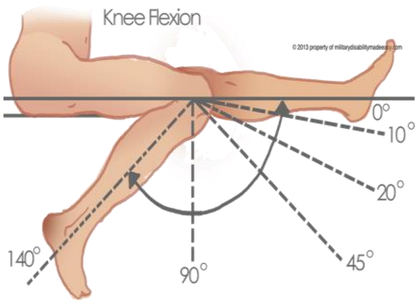

Figure 2. Shows seated knee flexion angles from 140-0˚ (Darcy, 2014)

Results from Eitzen et al (2010), concluded that the largest mean differences, occurred in angles of knee flexion at less than 40˚, this highlights the need to understand the full torque-angle window. Shimokochi and Shultz (2008), determined that most ACL injuries occur if the knee is close to or at full extension during combined motion (figure 1- [a]). However, the use of torque-angle analysis to provide a comprehensive strength profile is underrepresented in the available research with most studies including either PT solely and/or PT LSI thresholds as a key indicator of RTS readiness after ACLR. Further research into this area would give a greater understanding to an athlete's muscular strength profile, allowing an explicitly tailored approach to their rehabilitation, which can be characterized against normative values with future research and enhancing the reduction of future ACL injury.

2.2 ACL Incidence

ACL injury results in substantial time-loss from sport and significant financial burden. Injury incidence is substantially higher in level 1 sports (sports which involve jumping, pivoting, and CoD) and places high loads on the knee joint and soft tissue structures (Alentorn-Geli et al., 2009). Recent reviews from Fiblay and Grindem (2019) and Singh (2018), suggested that the incidence of ACL rupture in the USA alone stood at 250,000 individuals per year who require ACLR surgery. The rate of ACL ruptures is estimated at 30-78 per 100,000 people per year in the general population who play sport from Australia, New Zealand, and USA respectively (Bollen, 2005; Gianotti et al., 2009; Granan et al., 2009; Janssen et al., 2012). An injury surveillance study over a

10-year period conducted around National Collegiate Athletic Association (NCAA) sports found that ACL injury has been indicated at 1105 ACL ruptures per 350,416 athlete exposures (AEs) of which 126 were recurrent ruptures (Gans et al., 2018). Evidence by Ahmed et al (2017), shows that over a 12-year period of reporting ACL ruptures in a sport's orthopaedic clinic, roughly 28% of patients had sustained recurrent rupture of the ACL graft, which further supports the research on ACL graft rupture by Kyritsis et al (2016), who found that graft rupture rates of those who managed to complete RTS batteries (27%) compared to 73% who did not meet discharge criteria. These re-rupture rates coincide with previous research which highlights graft ruptures ranged from 6% to 25% (Barber-Westin & Noyes, 2011; Pinczewski et al., 2007; Webster et al., 2014; Wiggins et al., 2016).

Research from Grassi et al (2020), confirms around 10.7% secondary ACL injury after initial ACLR after a 10-year follow-up. With significant risk related to contralateral ACLR in the young and active patients with almost a 40% failure rate in grafts (Salmon et al., 2018; Webster et al., 2014). Further research from Montalvo et al (2019), found that the total incidence rates (IR) for contact sports were 1.51/10000 AEs, and that total IR for non-contact sport were a combined 0.25/10000 AEs for ACL ruptures like that of Gans et al (2018) research. A systematic review and meta-analysis by Chia et al (2022), also indicated that across 45 studies which covered 13 team ball-sports, non-contact ACL injuries (55%) accounted for all total ACL injuries. Chia et al (2022), summarises that overall non-contact ACL incidence was 0.07/1000 player hours and 0.05/1000 AEs which supports the higher volume of incidence rates found by Gans et al (2018) and Montalvo et al (2019). Statistically, injury incidence during competition was higher 0.48/1000 player hours and 0.32/1000 AEs compared with training 0.04/1000 player hours and 0.02/1000 AEs, these differences were significant (Chia et al., 2022).

2.2.1 ACL Incidence in Soccer

The incidence of soccer related injuries in the USA alone is estimated to be 10 to 35 per 1000 playing hours in adult males (Wong & Hong, 2005). A study by Dick et al (2007) suggested an ACL incidence rate of 1.0 to 1000 AE (games) and 0.10 per AE (training). This study was performed identically by Agel et al (2007), which reported less than 0.19 ACL injuries to 1000 AE (games) and 0.04 per 1000 AE (training). However, it should be noted these were collegiate female and male athletes respectively, who were not playing professionally compared to evidence found from Walden et al (2011). Walden et al (2011), suggested that in elite European professional soccer players, men's teams expected 0.4 ACL injuries per season and women 0.7 ACL injuries per season, which was also confirmed by Brophy et al (2012). The importance of identifying the incident rates of ACL injury is an increasing topic of research, especially when only 65% of professional soccer players return to pre-injury level three years after the injury (Walden et al., 2016). According to Grassi et al (2020), 84 ACL injuries occurred across seven consecutive seasons 2011/12 – 2017/18 in the Serie A (Italy). The overall incidence rate was found to be 0.06/1000 hours of play (combining training and matches) with no significant difference across seasons (P> 0.05). Interestingly the incidence proportion equated to 2.04% of total players involved within Serie A (20 teams) which equates to 0.6 ACL injuries per team every season comparable of research found by Walden et al (2011). Over a season this equates to an ACL injury expected every 72 Serie A matches. However, they did highlight a 14-fold risk increase in matches to training (Grassi et al., 2020). Furthermore, the study found that most ACL injuries occurred in the months of October and March with a 2-fold increase in those teams ranked 1st-4th place. Interestingly, this in turn could be due to the potential impact of success in their league position, thus, having to play more games due to European competitions. Zaffagnini et al (2014), also highlights that the age of male professional soccer players who undergo ACLR is 22.9 ± 5.4 years, which is attributable with existing literature for cohorts with ACL incidence rates within professional soccer (Grassi et al., 2020; Walden et al., 2015; Walden et al., 2016). The study also found that 95% athletes managed to RTS after 12 months and 62% were still playing professional soccer after four years post ACLR surgery. This would conclude that ACLR has become a successful outcome for these athletes, but further research via follow-up studies should be of interest to find out if these athletes still have any residual strength deficits after RTS. It would also be indicative to understand any injuries that have occurred within the knee or surrounding muscles such as hamstrings and quadriceps since RTS, as this could contribute to broader literature whilst giving an understanding if deficits are still present and how this affects injury increase after ACLR. This data would be good to use against athletes who have not undergone ACLR after ACL injury, however this type of literature is severely underrepresented in elite male soccer.

Finally, whilst there is a vast amount of data published regarding ACL injuries in professional male sports (Bisciotti et al., 2016) there is extremely sparse literature on ACL injuries in professional athletes from pivoting sports and soccer in the Gulf and Middle East countries. Rekik et al (2018), found that ACL injury rate amongst professional soccer players in the Middle East had an IR of 0.076/1000 AEs across a five-season study, which equated to 37 ACL ruptures. Rekik et al's (2018), study was comparable with literature on ACL IR (0.066/1000 hours of AEs) observed in the UEFA Elite Clubs study by Walden et al (2016), highlighting that ACL IR are comparable on different continents. For instance, this year alone across the top five European leagues (Serie A, Ligue 1, Bundesliga, English Premier League, and La Liga) there have been 35 ACL tears within a nine-month period alone (1st July 2021- 25th March 2022), with 45.7% of those 35 injuries coming from non-contact COD movements (Injury Mechanisms, 2022).

Although the ACL is the most studied knee injury with high volumes of published literature (Gianotti et al., 2009), while ACL injury research has been addressed significantly across Australasia, Europe, and USA it is evident in other populations and cultures the same research needs to be conducted (Rekik et al., 2018). Further research on Middle Eastern and Gulf populations in pivoting sports and professional soccer athletes can widely enhance the current spectrum of literature. It is prudent that ACL research provides a global approach especially with the ever-growing demand for soccer in the Middle East and Gulf countries, highlighted by the World Cup in Qatar to be held in November and December 2022. Evidencing the RTS characteristics and isokinetic testing protocols in these diverse populations will help provide a database that can be comparable to existing global literature and add to the evidence to create normative baseline data for athletes to safely RTS following ACLR.

2.3 Mechanisms for ACL injury

ACL injury mechanisms and loading patterns have been scrutinised over the years to try and determine any sequential patterns to further understand and mitigate ACL injury (Alentorn-Geli et al., 2009; Anderson et al., 2016). A systematic review from Della Villa et al (2020), suggests that 90% of ACL injuries over a ten-season period in professional Italian soccer, involved loading of the injured leg, with single limb loading on the ground mainly observed in 70% of cases. Furthermore, Della Villa et al (2020), found 44% were non-contact injuries (including no contact at the knee or any other body part), 44% indirect contact (an external force applied to the footballer but not directly to the injured knee) and 12% direct contact injuries (external force to the knee). Numerous studies report dynamic knee valgus, hip abduction, a flat and externally rotated foot and ipsilateral trunk lean as the primary mechanisms for non-contact ACL ruptures (Della Villa et al., 2020; Grassi et al., 2020; Koga et al., 2010; Walden et al., 2015). Previous literature stated that non-contact ACL injuries generally have a typical pattern the body follows at the time of rupture. This involves a valgus collapse of the knee joint, knee at near to full extension (0˚- 40˚), external tibial rotation with the foot planted while decelerating (Boden et al., 2009; Krosshaug et al., 2007; Quatnam & Hewett, 2009). Research highlighted that a direct blow happens less frequently than non-contact ACL injuries, corresponding with the 88% and 85% injuries which occurred without direct knee contact in respective studies (Della Villa et al., 2020; Walden et al., 2015). Generally, it is seen that the deceleration component when 'pressing' and CoD occurs on a single leg and this is the most prevalent issue for ACL injury (Alentorn-Geli et al., 2009; Della Villa et al., 2020; Krosshaug et al., 2007; Myklebust et al., 1998 & Walden et al., 2015). Research from Della Villa et al (2020) and Grassi et al (2020) analyzed 137 videos of ACL injuries in male professional soccer, looking into rapid posterior tibial reduction as a mechanism for injury. They found that this was consistently present alongside foot lifting from the ground and consistent degrees of knee flexion near or >90º for all late phases of non-contact ACL injuries in male soccer players. Although Grassi et al (2020) describe this as a purely theoretical viewpoint, the growing amount of video analysis in sport allows research to analyze injuries retrospectively, using slow motion video capture which will help to identify the MOI for ACL injury and the risk factors associated. Identifying the MOI helps with understanding where muscle strengthening is needed during planes of movement to address these areas of weakness in a sport performance perspective.

2.4 Risk Factors for ACL Injury and Re-Injury

With most of the research indicating that most ACL injuries occur through non-contact scenarios, research should focus around the potential modifiable risk factors that can be altered and adapted to help reduce the rates of ACL injury. The two most common mechanisms of ACL injury during multidirectional field-based sports are deceleration and landing (Montalavo et al., 2019). With H:Q torque production becoming an established variable into primary ACL injury risk modelling (Myer et al., 2010a and Myer et al., 2011) it is important that we further understand the underlying strength deficits that may continue to persist after ACLR (Di Stasi, Myer & Hewett, 2013). Therefore, research needs to ascertain how risk factors may affect the way in which ACL injuries occur, but also how these factors can be utilized to increase the percentage of athletes who RTS at the same level they sustained the injury. Risk factors such as biomechanical patterns, MOI, lack of muscular strength or imbalances can all be contributing factors to ACL injury as mentioned earlier.

2.4.1 Ancillary Risk Factors Associated with ACL Injury

Modifiable risk factors for non-contact injuries can be explored to help reduce the number of ACL incidents. Most investigations of ACL injury tend to follow the methodologies of Bahr & Krosshaug (2005) (Figure 3). A variety of ways to understand the MOI allows for a greater representation and understanding of how and why ACL injuries occur. Recent literature uses an experimental design and looks to highlight potential risk factors using video analysis and biomechanical experiments (Della Villa et al., 2020; Grassi et al., 2020). It is important to use a variety of methodologies when trying to investigate research to obtain quantitative and qualitative findings, which help to form future direction of research in RTS after ACLR. Previous research from Myer et al (2011) used predictive algorithms to identify those who had an increased risk of ACL injury. However, no one single form is perfect and each have their own limitations, for example: video analysis of ACL injury can be difficult to identify the exact timeframe the injury occurs, but it also relies on the video footage quality (Quatnam et al, 2010). Nevertheless, due to the nature of ACL incidence most studies are conducted with a longitudinal design due to the timeframe from injury to RTS. This allows a multitude of different analyses of risk factors to be assessed because of the injury audit timeframe which often is carried out over 2-5year periods of research.

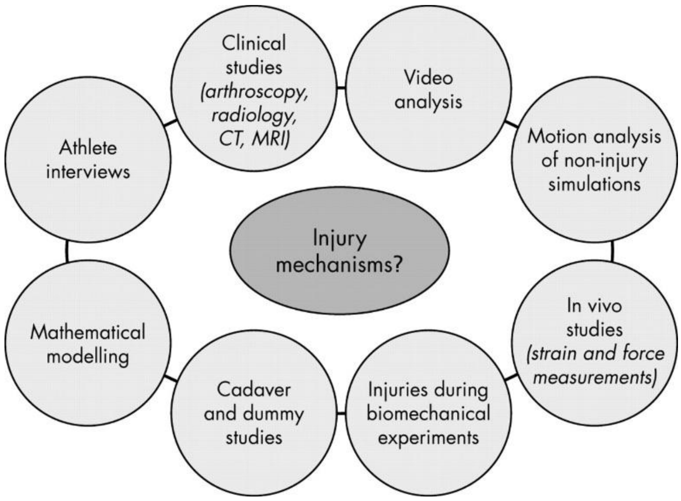

Figure 3. *Research approaches to describe the mechanisms of injury in sport and how to identify future risk factors of injury. (Krosshaug et al., 2005)*

Knee Valgus and Rotation

Dynamic knee valgus is the most reported and described MOI for ACL injury (Alentorn-Geli et al., 2009; Della Villa et al., 2020 & Koga et al., 2010). Knee valgus has long been associated as a predictive risk factor for ACL injury in female athletes during drop jump assessments (Hewett et al., 2005; Hewett et al., 2006). It is an influencing factor in female's who are almost 5.3 times more likely than male counterparts to demonstrate knee valgus due to their genetic make-up; 83% of males demonstrated no valgus collapse during injury (Krosshaug et al., 2007). Whilst knee valgus loading is known to increase the strain on the ACL, it is the angle and position of the knee that is of most influence. Peak knee valgus angle and landing in a valgus position has greater impact on ACL strain than purely valgus moments (Grassi et al., 2020 & Withrow et al., 2006;). Internal tibial rotation increases ACL loading throughout all knee flexion angles when weightbearing (Fleming et al., 2001) compared with that of external rotation that offsets the ACL (Shimokochi & Shultz, 2008). It is generally assumed that when knee valgus is demonstrated alongside knee internal rotation and combined with anterior tibial shear this produces the greatest strain on the ACL (Shimokochi et al., 2013). The angle of the knee is often associated with the load the knee can absorb during ground contact. If the knee is at 120^{o} flexion, the fibres run parallel to the tibia, this allowing the ACL to withstand more strain. The greater knee extension the greater the transverse load across the ligament (Herzog & Read, 1993). The hamstrings, ACL, adductor magnus and soleus all play a key component in resistance of anterior tibial translation (ATT). ATT at 30˚ knee flexion provides almost 85% of resistance of the movement, with maximal loads seen at 15-30˚ knee flexion (Olsen et al., 2004). Moreover, the hamstrings have greater influence when the knee is more flexed, but they cannot resist anterior shear in full knee extension (Herzog & Read., 1993). The hamstrings are most effective between knee angles of 15-60˚ to reduce anterior tibial movement (Li et al., 1999). The quadriceps (antagonists of ACL) produce and increase anterior tibial translation forces when the knee is relatively close to full extension, causing ACL strain. Conversely, the hamstrings act as agonists for the ACL, to reduce the ATT so decreasing strain on the ACL (Podraza and White, 2010; Shimokochi & Shultz., 2008). ACL injury can be due to the force-length relationship as PT of the hamstrings will be around 30˚ and quadriceps around 60˚ which needs considering for ACL injury (Croisser et al., 2002; Grygorowicz et al., 2017; Hohmann, Tetsworth & Glatt, 2019; Yeung, Suen & Yeung, 2009).

Genetic Factors

The ACL attaches from the front of the tibial plateau, runs backwards and side-wards to attach onto the femur, measuring between 25-35mm in length. The anatomical structure of the ACL can compromise and highlight the risk of a potential ACL rupture. Non-modifiable intrinsic risk factors such as tibial slope, notch width, and femoral condyle shape have all been correlated with 1.98 (females) and 1.76 (males) times increased risk of ACL injury (Sturnick et al., 2015). Sturnick et al (2015) also found that from using a multivariate modelling system which incorporated femoral notch width at the anterior aspect, combined with lateral compartment middle cartilage slope as a high ACL injury risk, concluding that each millimeter decrease in femoral notch and each degree increase of slope in lateral compartment of the tibia produced 50% and 32% increase in risk of ACL injury. However, compared with male counterparts the variables highlighted in the multivariate model combined volume of the ACL and the lateral compartment meniscus bone angle. They reported for each $0.1cm^3$ decrease in ACL volume and each degree decrease in slope angle of the meniscus this resulted in 43% and 23% increase in risk of ACL injury.

Graft Types

It is postulated that ACLR surgery is the 'gold standard' for ACL injury for those who want to regain previous sporting level where activities include hard cutting, pivoting and CoD (Grindem et al., 2016) but non-surgical management is also an option that can be taken, and is advised if there is no instability in the knee. Bone-patellar tendon-bone (BPTB), hamstring and quadriceps tendon autografts are the most used methods for ACLR, but the choice of graft type also strongly depends on the surgeon's personal preferences (Goldblatt et al., 2005). Other factors such as athlete centred approach and ability to restore function again after ACLR should also be taken into consideration. While a surgeon's preference may warrant a certain surgical procedure it needs to be confirmed with all parties involved. This shared decision-making process should take place to understand what is best for the athlete. For instance, if we took a soccer player or 100m sprinter and suggested both to have HS grafts over BPTB, we would need to understand the connotations this would have on recovery and athletic performance over the early and late-stage rehabilitation. When considering which graft type to use, there are several considerations including failure rates, sport demands, physical deficits, and patient history. Research indicates graft failure rates are only marginally different according to a meta-analysis from Samuelsen et al (2017); they claimed that BPTB graft failure rates were 2.8% (212/7560 patients) compared to HS graft failure at 2.84% (1123/39,510 patients). A systematic review from Hayback, Raas and Rosenberger, (2021) looked across 194 studies and found that there was no significant difference across graft failure rates. They postulated that HS graft (1.70%), BPTB (1.16%), quadriceps tendon (0.72%) and allografts (1.76%) had these yearly figures for graft failure rates. HS grafts allow for earlier re-introduction of quadricep dominant exercise in the early stage of rehabilitation before introducing hamstring rehabilitation around week 6-8 (Schoenfeld et., 2020). BPTB grafts do allow for early intervention of quadricep exercises to try and restore terminal knee extension (Ebert et al., 2021). HS grafts are associated with lower donor site morbidity, reduced anterior knee pain and smaller extensor strength deficits (Freedman et al., 2003; Li et al., 2012; Mohtadi et al., 2015). However, it should be noted that in the longer-term, donor site morbidity seems to be present amongst all graft types within the earlier stages of rehabilitation and so is prudent to identify open and closed kinetic chain exercises to have early restoration and function of quadriceps and hamstrings to help protect and strengthen the structures surrounding the ACL. This evidence supports the need for strong quadriceps as an indicator to reducing the chance of re-injury (Grindem et al., 2016). BPTB grafts may also display less knee joint laxity and knee extension strength deficits compared with a HS graft, which significantly reduces the chance of knee flexion strength deficits and residual patellofemoral pain and faster graft incorporation (Goldblatt et al., 2005 & Papageorgiou et al., 2001). Therefore, wider research should be conducted in this area to further understand contributing factors associated with graft type failure rates and associated strength deficits. Specifically, identifying strength imbalances which can be apparent based on graft type using a comprehensive strength profile assessment, this can assist clinicians to design targeted rehabilitation programs and reduce muscular deficits before the athlete's RTS.

2.5 Assessments for Returning to Sport (RTS) after ACLR

RTS decision-making following ACLR is a complex and multifaceted process and time from surgery has traditionally been used as the main determinant (Burgi et al., 2019). A criterion-based approach is now recommended, with some evidence indicating that passing a battery of tests reduces risk of re-injury (Grindem et al., 2016 & Kyritsis et al., 2016). RTS rates appear to be higher in elite sport as shown by Lai et al (2017), who observed a pooled rate of 83%, and this mirrors previous findings (Ardern et al., 2014). However, these findings indicate a significant number of athletes do not return to sport. In addition, 1 in 5 athletes sustain a reinjury to the graft or contralateral rupture predominantly within the first year after RTS (Barber-Westin and Noyes., 2020; Hewett, Myer & Ford, 2006; Wiggins et al., 2016). Thus, current assessments used to assess athletes' readiness to RTS may warrant critical examination.

At the time of discharge from rehabilitation prior to RTS, certain criteria must be met. LSI has been most used, which is a ratio of the distance hopped on the involved limb and uninvolved limb, measured during a series of single leg hops and isokinetic tests of quadriceps and hamstrings strength (Webster & Hewett, 2019). When expressed as a percentage, values >90% are required to 'pass' with evidence suggesting this reduces the risk of re-injury (Grindem et al., 2016 & Kyritsis et al., 2016). Kyritsis et al (2016), found that athletes who did not complete the six discharge criteria were 1.9-9.2 times more likely to have an increase of ACL graft rupture with the average increase hazard ratio (HR) being 4.1 times increase of ACL graft rupture (HR 4.1, 95% CI 1.9 to 9.2 p≤0.001). Webster and Hewett (2019) conducted a systematic review and meta-analysis of RTS testing and they found that two studies showed passing RTS test batteries did not significantly reduce risk of a further knee injury (risk ratio (RR)=0.28 (95% CI 0.04-0.94), p=0.09). A further five studies showed that passing RTS test batteries did not reduce risk for all subsequent ACL injuries (RR=0.80 (95% CI 0.27-2,3), p=0.7) (Webster & Hewett, 2019). Additionally, Webster and Hewett (2019) stated minimal evidence was present that patients passing a RTS test battery significantly reduced the risk of any subsequent knee injuries including ACL injuries. When critiquing the meta-analysis from Webster and Hewett (2019) caution needs to be applied as their results suggest various studies used different criteria for cut-off values. Toole et al (2017), highlighted that passing a battery of tests is a 'penalty' because most tests had to meet a pass rate at 90%. For instance, if athletes passed a test at 90% and then a second test at 90% and so forth, then naturally the number of athletes who pass RTS tests will drop (Toole et al., 2017). Within Webster and Hewett's (2019) meta-analysis it should be noted that different cohorts were used in different studies that they analysed. Also, one study (Beischer et al, 2018) only had 29% of patients achieving >90% LSI on five tests of muscle function, despite already RTS at 8months.Webster and Hewett (2019) found that passing a battery RTS tests significantly decreased the risk of a graft rupture but astonishingly increased the risk of contralateral ACL injury by 235%. These findings must be interpreted with care due to the nature of mixed findings and the heterogenous pooling of the data. Subsequently, it is worth noting that findings only come from a couple of studies and when you look at the weightings on the forest plots it appears that those returning in and around 6 months were more likely to re-injure. Consequently, the information that can be applied clinically from these results has to be questionable because of the high level of uncertainty and validity in which research was conducted across various studies.

2.5.1 Time as an Indicator for RTS and Highlighting Residual Deficits

Nagelli and Hewett (2017), argue a two-year timeframe would be plausible for RTS after ACLR due to graft sensitivity and healing on a cellular level, which can take up to 24 months to yield adaptations and reduce re-injury risks after primary ACLR. However, it is illogical and impractical for elite athletes to take up-to two years out of their respective sports plus the financial constraints it puts on their clubs. This would not only have severe psychological implications for competitive athletes including disruptions in mood states, a loss of positive social identity and uncertainties regarding the prospects of a return to pre-injury competitive levels after serious longer-term injury such as ACL (Bianco., 2001; Forsdyke et al., 2016 & Gould et al., 1997). Whilst considering the psychological impact of ACL injury there is also no evidence that delaying RTS for ~ 2 years reduces the risk of graft re-rupture or subsequent contralateral ACL. Grindem et al (2016), highlight the importance of the association between increased quadriceps strength and the reduced risk of injury, suggesting that there is a 3% reduced re-injury rate for every 1% point increase of strength symmetry. Grindem et al (2016), underline the pivotal role of delaying RTS during the first nine months post ACLR stipulating that for each month RTS was delayed re-injury rate reduced by 51%. Re-injury rates for elite athletes who RTS earlier than nine months were 39.5% (15/38) compared with 19.4% (7/36) athletes that RTS after nine months. Subsequently, clinicians should be working with athletes to help them understand the benefits of reducing re-injury rates by not RTS prior to nine months. Many athletes will not adhere to 24 months before RTS and there is no evidence to suggest this milestone would further reduce re-injury rates from Grindem et al (2016) work. Therefore, whilst time is traditionally the marker of RTS after ACLR there are other testing protocols that need to be applied through the nine-month rehabilitation period for athletes to RTS.

Whilst we understand time is a benefitting factor to reducing re-injury, we need to be aware that other milestones need to be hit. For instance, just because an athlete has not RTS for nine months it also has to be evident that they are physically strong enough to RTS. This can and should be tested via numerous strength testing procedures. As clinicians if a nine month timeframe has been identified to RTS, but an athlete's strength scores are only 80% of the non-injured limb you are increasing the risk of re-injury dramatically by returning the athlete purely based on a time-based decision. Quadriceps strength should be a priority for discharge criteria after ACLR and should work off a LSI of >90% before RTS. Grindem et al (2016), study found that of 15/45 (33.3%) patients who returned to level I sport with LSI<90% suffered a re-injury compared with 3/24 re-injuries (12.5%) of patients who had quadriceps LSI>90%. This further reinforces that LSI of >90% quadriceps strength is a non-negotiable when safely clearing an athlete to RTS, which this study aims to illustrate through the analysis of torque production across a torque angle window. Whilst time as a metric has been heavily researched and reported, as a primary objective to follow within the RTS continuum to reduce risk of future ACL injury, there are still many athletes who do not RTS or do not return to their previous playing level.

Therefore, as researchers we must further scrutinise other factors that may be contributing to the downfall of athletes RTS. If athletes are meeting what is classified in the literature as 'optimal' timeframes of 9-12 months for RTS after ACLR but are not managing to RTS at their previous level or sustain secondary ACL injuries, then we must delve deeper into aspects such as biomechanical, psychological and strength as factors that potentially are limiting athletes from RTS at pre-injury level. Due to the prevalent role hamstrings and quadriceps play in the rehabilitation from ACLR and the general nature that the strength of these muscles have in helping to reduce further ACL reinjury (Grindem et al., 2016) it highlights the need to use muscular strength testing as a concept to form a crucial part of the RTS testing protocol after ACLR.

2.5.2 Strength as a Key Indicator for Passing RTS Testing

Restoration of strength, power, and neuromuscular control assessments are a prominent fixture throughout the rehabilitation process. Buckthorpe and Della Villa (2020) highlight that functional strength is the ability to produce and absorb force in situations where muscles are commonly used, such as landing and cutting movements. If an athlete then has strength deficits in knee extension and flexion angles, this highlights the potential for ACL injury risk if the correct restoration of strength, power and neuromuscular strength is not observed. Reduced capacity of knee extension strength will mean that an athlete would adopt compensatory movement patterns, usually utilizing the hip extensors more than the knee extensors (Salem, Salinas & Harding, 2003; Sigward et al., 2018) resulting in reduced neuromuscular recruitment and increased injury risk. The quadriceps and hamstrings as we know play a crucial role in knee joint stability and there is a reliance on these muscles to increase joint contact forces and reduce shearing load which could increase ACL strain. Studies have found that in the majority of ACLR patients, strength deficits take a prolonged period to be ascertained and are regained over approximately five years following ACL injury (Palmieri-Smith, Thomas & Wojitys, 2008). However, Ageberg, Patterson and Friden, (2007); Fink et al., (2001); Risberg et al., (2016) and Tengmen et al., (2014) state that deficits ranging from 3.5-12% can be found in quadriceps strength more than 10 years later in patients. Research has shown that the influence of quadriceps force is dependent on the knee flexion angle. In lower knee flexion angles <30˚-50˚ the quadriceps induce a lot of shearing loads on the ACL structures and at higher angles of 80˚ often have a limited role to play other than to serve off-loading the structure (Maniar et al., 2022). Therefore, we need to incorporate quadriceps muscle strength as one of the main requirements post ACLR, because tasks including side-stepping and cutting movements when the quadriceps force vector is producing the most force can put anterior shearing load on the ACL (Maniar et al., 2022). Conversely, angles of 20˚- 30˚ are where the hamstring produces peak forces which enable a posterior shearing force, which unloads the ACL (Guelich et al., 2016 & MacWilliams et al., 1999). Understanding this helps to identify why the hamstrings are at a disadvantage compared to the stronger mechanically advantaged quadriceps (Krosshaug et al., 2007).

Consequently, testing of these components can assist with determining progress and identifying areas for strength development which may be associated with injury risk. Mitigating re-injury risk after ACLR is of high importance to the athlete and clinician. Grindem et al., (2016) stated that increasing strength and strength symmetry may be important to negate future injury and reduce the chance of re-rupture. We know that when athletes undergo ACLR these qualities are affected significantly, and they come hand in hand. Equally, asymmetry of the quadriceps can result in asymmetrical biomechanics during hopping tasks which can lead to an increased risk to ACL injury due to the forces and perbutations involved (Palmieri-Smith & Lepley., 2015). Grindem et al., (2016), also found that a quadriceps weakness was a resulting risk factor in the increase in osteoarthritis. They suggest that quadriceps are of high importance through the rehabilitation process and quadriceps strength assessment prior to RTS. Altered muscle strength of the quadriceps and hamstrings can result in poor postural control around the hip, knee and trunk meaning a predisposition of future ACL injury (Paterno et al., 2010). Additionally, Kyritsis et al (2016), found a 10.6 times increased risk of ACL graft rupture for every 10% difference recorded at 60˚/s in H:Q ratio in male Qatari soccer players. Identifying these strength discrepancies prior to and post ACLR can allow clinicians to implement strength exercises to mediate such weakness. Furthermore, when returning to sport we know that the contralateral limb is affected in the same principles as the reconstructed knee and this is why sometimes the involved limb can have over-estimated knee function when using LSI (Buckthorpe, De la Rosa & Della Villa., 2019). Compiling future research should look to ascertain muscle strength and activation, sensorimotor control and how this can affect biomechanical movement patterns after ACLR (Constrom, Tengman & Hager., 2022). This would further enhance the post-operative rehabilitation care given to athletes to make sure they exert full muscular strength function before being RTS after ACLR.

2.5.3 Hop Tests for Strength Indication as a Comparable for LSI on Isokinetic Testing

Much focus of strength testing has come through the assessment of hop tests and jump tests, whilst knowing that these types of movement are increasingly important to determine functional strength recovery after ACLR. The mechanisms associated with hoping testing such as take-off and landing are aspects that occur during ACL MOI and therefore need to be addressed for functional relevance to discharge and return athletes safely to sport (Alentorn-Geli et al., 2009 & Disteffano et al., 2015). ACLR is known to alter jumping and landing patterns in both the involved and uninvolved limbs (Marshall et al., 2015; Nagal et al., 2019). Single leg hop for distance (SLHD) and triple hop tests for distance (THFD) are used and have been validated for clinical use in patients who have undergone ACLR for many years (Noyes, Barber & Maringe, 1991). Recent research has found that whilst SLHD provides an insight to symmetry in performance it does not validate symmetry in lower limb biomechanics post ACLR (Kotsifaki et al., 2022). This study suggested that SLHD is a poor measurement of knee function on RTS testing as it ultimately reflects greater hip and ankle function than that of the knee. Kotsifaki et al (2022) conducted video analysis (3D motion) and electromyography (EMG) in 26 male ACLR patients and 23 male healthy controls when performing a SLHD to calculate lower limb kinematics and work at the three joints. Significant differences were found in between groups, ACLR athletes showed a 97% ±4% LSI when analysing distance, however, when looking at work conducted by the knee during propulsion only 69% symmetry occurred in ACLR athletes. This study highlighted the involved knee absorbed less work than the uninvolved knee during landing mechanics; the uninvolved knee also absorbed more force when compared with the control group. This emphasised the issue that ACLR athletes effectively compensate for lower knee force production and absorption by allowing the hip to produce greater work and when landing they allow greater hip and trunk flexion to absorb the forces (Kotsifaki et al., 2021). Paterno et al (2010) identified during a double leg drop jump (DLDJ) that hip rotation moment, frontal plane knee range of motion during stance phase, asymmetry of knee extension moment at initial contact and postural stability could predict second ACL injury with a sensitivity score of 0.92 and a specificity score of 0.88. This reiterates the information found by Kotsifaki et al (2022) that hip and knee moment forces can cause ACL injury and specifically the risk of secondary ACL injury according to Paterno et al (2010). Subsequently, future research would need to investigate further into vertical hop testing to identify biomechanical floors in jumping and landing mechanics as these may highlight greater asymmetries than hopping for distance, especially when advanced equipment is not readily available (Kotsifaki et al., 2022). Using this information on hop testing as a measure of strength allows for a coherent comparison with isokinetic strength testing. Ultimately, providing data of force production under both concentric/concentric (CON/CON) and concentric/eccentric (CON/ECC) actions which will translate into useful information for further identifying any biomechanical and strength deficiencies in hopping tasks whilst assessing how to improve potential rates of force development (RFD). Consequently, it would be prudent to further the research into isokinetic strength testing. Isolating strength testing as part of a battery of tests would potentially lead to a greater symmetrical strength bilaterally by having more than one metric to compare against each other, both in a functional and task orientated position that directly links to where the MOI occurs. The use of isokinetic strength testing has the potential to identify strength deficits throughout a complete RoM and across a time-specific window (e.g., 5/10/20secs) (Undheim et al., 2015; Baumgart et al., 2018). Analysing angle-specific strength allows clinicians to profile, enhance, and focus rehabilitation in specific RoM where deficits are highlighted. Resulting in trying to minimise and equal force distribution from limb to limb and a decrease in greater work produced by the hip and the uninvolved knee when assessing muscle strength through testing batteries such as SLHD and vertical jump analysis. In turn isokinetic assessment can help towards leading to a comprehensive structure for enhancing RTS criteria and testing protocols during ACL rehabilitation.

2.6 Isokinetic Assessment

An isokinetic dynamometer (IKD) can measure in both eccentric and concentric contraction modes and at different velocities. Keeping and maintaining a constant force, the IKD can also resist against a force generated by an athlete depending on the mode of contraction Con and Ecc that is being performed (Osternig, 2000; Udheim et al., 2015). Isokinetic testing has been shown to yield reproducible and reliable measurements for knee extension and flexion torque (measured in newton meters) after ACLR, providing an indication of quadriceps and hamstring strength (Undheim et al., 2015). This type of testing will show consistent deficits in quadriceps and hamstring strength after ACLR which provides further validity to assessment criteria. The most tested angular velocity is 60˚/s on IKD testing protocol in ACLR RTS. Previous research has primarily looked at testing specific torque angles at concentric and eccentric contractions. Strength discrepancies are often highlighted at 60˚/s (Risberg et al., 2007 & Thomas et al., 2013). Torque output decreases as angular velocity increases beyond 60˚/s, therefore, highlighting the strength discrepancies becomes difficult to do. Whereas keeping the angular velocity at 60˚/s when analysing torque angles, highlights any irregularities in strength (Undheim et al., 2015). Angular velocities at higher speeds such as 240˚/s and 300˚/s are questionable but replicate dynamic movements such as kicking a football. As the isokinetic period is very short when the lever arm needs to accelerate to reach required velocity and then decelerate before reversing the motion (Lepley, 2015) it is difficult to identify strength deficits in these high-speed velocities even though they are functional to sport performance. Although less quadriceps strength asymmetries are present at higher velocities it does not mitigate the deficits at slower angular velocities. The most common angular velocities used in isokinetic assessment are 60˚/s, 120˚/s, 180˚/s, 240˚/s and 300˚/s with 60˚/s the ideal testing protocol (Undheim et al., 2015). The faster velocity contractions have limitations that prove difficult to analyse the data and make any assumption to the population. Undheim et al (2015), identify that testing at higher angular velocity speeds has lower reliability due to the rapid contractions that occur. Due to these speeds inertial effects are more prominent in these types of testing procedures making the data harder to interpret (Undheim et al., 2015). There is also data to suggest that slower isokinetic speeds (60˚/s) correlate with functional tests such as hopping (Petschnig et al., 1998) but just not explosive sport performance such as kicking a ball. This concurs with other research which highlights again the slower the angular velocity speed the greater strength deficits are identified; 60˚/s, has been shown to identify strength asymmetries than higher velocity such as 120˚/s, 180˚/s and 300˚/s (Lepley., 2015 & Undheim et al., 2015).

2.6.1 The Use of Isokinetic Testing after ACLR

When testing for isokinetic strength after ACLR, athletes are specifically looking to be testing and assessing the muscular strength of the hamstrings and quadriceps at a set RoM (0˚- 90˚). Undheim et al (2015) suggest eccentric testing shows a greater torque value than concentric testing, this is because of the muscle physiology due to the force/velocity relationship. Consequently, they may provide a rigorous objective assessment measure but that is all dependant on what the goal and outcome is. If the data output is solely looking at PT alone, then both eccentric and concentric values will be highly correlated. However, due to the difficulty of the testing procedure a familiarisation session maybe required for eccentric testing; due to this, reliability and reproducibility of eccentric testing is lower when compared with concentric protocols (Undheim et al., 2015). There is an abundance of data on CON and ECC muscle testing and depending on what the goal and function of the data output is would be dependent on what mode of contraction you would use. This may be more comparable to highlight knee muscular function as a metric than ECC testing which would potentially require multiple sessions for athletes to get used to the testing procedure. Further ECC isokinetic testing is an area in which future research should be encouraged, as this type of movement occurs in many sporting actions such as deceleration and CoD and is also potentially linked to dynamic stabilisation as mentioned earlier in this literature review. Undheim et al (2015) recommend that the ideal use of isokinetic testing after ACLR is testing con/con with an angular velocity of 60˚/s, from 0˚ - 90˚ knee flexion angle, for 3-5 repetitions with gravity correction as the most useful testing protocol for RTS testing after ACLR. Previous research suggests 3-5reps for isokinetic strength testing is routine for assessing the knee extension/knee flexion when working CON/ECC strength (Eitzen et al., 2010; Huang et al., 2017; Pelegrinelli et al., 2018).

2.6.2 Strength Testing Post ACLR Surgery

The most common strength testing procedure conducted in RTS test batteries is isokinetic strength testing (IKD), suggested to be the 'gold standard' for assessing single joint muscle strength due to its strong reliability and reproducibility (Undheim et al., 2015). A systematic review from Undheim et al (2015) proposed IKD analyses reports PT as the most common isokinetic variable reported; whilst utilising an LSI to determine a percentage difference of muscle strength between the uninvolved and involved limbs. Strength deficits within the quadriceps and hamstrings are often an expected consequence of ACLR (Baumgart et al., 2018; Grindem et al., 2016; King et al., 2019; Kyritsis et al., 2016; Read et al., 2021; Webster & Hewett, 2019). This can be due to numerous ancillary issues that have already been identified such as grafts, rehabilitation, and stage of rehabilitation. Arthrogenic muscle inhibition (AMI) is hypothesized to be present after ACLR and contribute to the ever-present post-traumatic knee extensor muscle strength deficits. AMI inhibits intensity levels and neuromuscular activation, which is present bilaterally after unilateral ACLR, in cases equivalent to injured limb (Buckthorpe et al., 2019). Thomas et al., (2013) study which featured a case control on 15 individuals who sustained ACL injury (m=8, F=7) and 15 healthy controls (M=7, F=8), found that patients who had ACL injury had greater knee extensor and flexor weaknesses post-operatively, which was conclusive of other research findings. AMI ultimately can cause weakness in muscle restoration and therefore result in weakness in these muscles, thus, impairing knee joint stability. This proves the need to warrant appropriate and targeted rehab to the knee extensors and flexors, in order to 'pass' isokinetic strength testing at the point of RTS after ACLR but also to indicate how torque-angle analysis of muscle strength can provide a greater insight to where muscles are lacking in muscular strength.

Due to muscular strength imbalances between quadriceps and hamstring muscles it often gives a disproportionate H:Q ratio which as highlighted previously can be a primary cause for ACL injury (Buckthorpe, La Rosa & Della Villa., 2019; Kellis, Galanis & Kofotolis., 2019). Evidently, Tayfur et al's (2021), meta-analysis continued to highlight persistent deficits between quadriceps and hamstrings strength in the short term and longer term (<6months, >2years) after ACLR due to the neuromuscular changes that were found after unilateral injury, specifically AMI which resulted in these changes. It should also be considered that the H:Q ratio after ACLR in the traditional method has inherent limitations due to the observed quadricep differences (markedly reduce on the involved limb which artificially increases the H:Q ratio), and the no major differences between limbs in hamstring strength following the early stages of rehabilitation, especially in those athletes who have BPTB grafts (Renner et al., 2018 & Samuelsen et al., 2017). IKD strength testing can include both CON and ECC muscle contractions, modes of muscular contraction that occur regularly in sport and dynamic knee stabilisation. The importance therefore of collecting CON and ECC data is so that we can contextualise to sporting activity. The majority of data collected in research is CON with more research being conducted on ECC modes of contraction too. Assessing this data using H:Q ratios through conventional and functional ratios (CON/CON and ECC/CON) enables clinicians to highlight strength imbalances before RTS. Cohen et al (2015) and Ruas et al (2019) stated the use of the FR is an alternative method to the use of the conventional ratio and offers a greater insight to the potential deficits that are occurring after ACLR. However, due to the extensive H:Q conventional ratio data this study decided to still incorporate the use of this method to compare to previous literature. It was also incorporated so that it could be assessed against each 10˚ segment and against angle-specific torque FR and conventional ratios.

Evidence of more ECC data would yield data which is needed when comparing to running based actions where 80% hamstring activity is performed in ECC contractions (Chumonov, Heiderscheit & Thelen., 2011). Although, van Hoovern and Bosch (2017) devise that there may be more isometric action of the hamstrings than ECC during the swing phase of running. However, it is evident that pivoting and accelerating and deceleration require large demands of ECC activity of the knee flexion (van Melik., 2017). The relevance to this is these actions frequently occur in level 1 sports like soccer and are also identified as a key MOI for ACL injury (Della Villa et al., 2020). Unilateral reductions in strength and inter-limb asymmetries appear to be associated with reductions in the performance of sport-specific tasks including CoD, jumping, and landing (Bishop, Turner & Read., 2017), all of which relate to primary mechanisms of ACL injury (Walden et al., 2015). Thus, requiring more evidence to further understand ECC strength demands in relation to sporting movements that occur during ACL injury. As mentioned in isokinetic section analysis of concentric and eccentric contractions throughout a RoM conducted at IKD testing can be done at different angular velocities to replicate the demands during sport, which can then be attributed for running drills post ACLR.

2.6.3 Use of limb symmetry index following ACLR and observed limitations.

Previous research has suggested that an LSI >90% has been used to define functional recovery (Abrams et al., 2014), and as a 'pass' criterion in RTS decisions following ACLR (Grindem et al., 2016; Kyritsis et al., 2016). However, using the contralateral limb at the time of discharge as an index in the calculation of LSI assumes this limb is deemed an acceptable standard (Benjaminse, Holden & Myer., 2018; Wellsandt, Failla & Synder-Mackler., 2017). Evidence suggests estimated pre-injury capacity (EPIC) values are not met when assessing knee extensor strength to pass RTS criteria (Wellsandt, Failla & Synder-Mackler, 2017). Specifically, patients who achieved > 90% LSI on all strength measures six months post ACLR did not achieve 90% EPIC levels (using pre-operative scores on the un-involved limb) (Wellsandt, Failla & Synder-Mackler, 2017). Thus, traditional use of LSI (comparing between-limb scores at the time of discharge following ACLR rehabilitation) may overestimate knee function. Emerging evidence indicates that peripheral joint injuries should be viewed as a neurophysiological dysfunction, not simply a local injury (Ward et al., 2015). Central nervous system reorganization may result in neuromuscular deficits after injury resulting in muscle weakness bilaterally. Therefore, current use of LSI using PT alone has the potential to mask residual deficits and highlights the importance of including a strength profile. Future research could examine if athletes who 'pass' IKD testing using a traditional approach of including PT and LSI only, display specific deficits across different torque-angle windows during the tested RoM.

2.6.4 Strength Profiling: Torque-Angle Specific Windows

A limitation in the sole use of conventional PT values is that it only provides a scaler quantity for a single time-point on a torque/time/angle curve rather than examining continuous data during the full RoM (Baumgart et al., 2018; Huang et al., 2017 & Rambaud et al., 2018). An alternative approach is to include a more comprehensive strength profile, considering specific torque-angle values (Rambaud et al., 2018). This allows clinicians to not only quantify a between-limb deficit, but also to characterise it (Read et al., 2021). This has connotations for athletic individuals following ACLR as deficits may be more pronounced during certain RoM. El-Ashker et al (2017), suggest the need to examine H:Q ratio closer to full knee extension as it more closely resembles the mechanism of ACL injury, rather than just using a singular PT value, without considering the angle at which it occurs. When using a traditional/conventional ratio (CON:CON) using PT, the angle of PT is different for the quadriceps and hamstrings and occurs at two different points on the torque-angle curve and this does not provide an accurate representation of dynamic knee stabilization. When considering the force length relationship, the hamstrings are at a more advantageous position when the knee is closer to extension (hence higher torque) whereas the knee extensors are optimised around 60°. Therefore, saying the ratio should be 0.6 (Coombs & Garbutt., 2002) for example is not ideal as the ratio can range considerably depending on the joint angle tested. Evidence would suggest that ratios closer to 1.0 would be an optimal ratio (Ruas et al., 2019).

There is limited evidence available using an isokinetic strength profile approach in which torque throughout the tested RoM is examined. Baumgart et al (2018) and Read et al (2021), identified significant differences between the injured and uninjured limb in knee flexion angles from 50˚- 80˚. It should be noted that participants (n=38, f=18 and m=20) in Baumgart et al's (2018) study were all team sports athletes who had undergone unilateral HS grafts compared with Read et al (2021), who were 27 male athletes competing in professional soccer of which 70% had BPTB grafts and 30% had HS grafts. Yet, H:Q ratios of the operated leg were generally greater throughout the RoM (Baumgart et al., 2018 & Read et al., 2021). This could be due to observed quadriceps weakness after ACLR, thus traditional H:Q ratios may well be suggesting a diminished value. Angle specific testing can reveal more information than conventional PT values and H:Q ratios (Eitzen et al., 2010; Hiemstra et al., 2007), torque-angle curves of the knee extensors and knee flexors have different shapes which are dependent on angular change in H:Q ratios. Consequently, conventional H:Q ratios which are conducted using a PT value cannot represent the shape of angle-specific H:Q ratios, compared to torque-angle analysis, which allows a complete view of quadricep torque values through knee extensor RoM providing a complete isokinetic strength profile (Eitzen et al., 2010). Additionally, the use of H:Q ratios could still provide useful information when identified at angle-specific windows for both conventional and FR. Using low velocities allows for the set RoM to be covered at the set velocity of 60˚/s (Dvir, 2004; Kurdak et al., 2005). Eitzen et al (2010) discovered that PT values differed by 1˚ between the injured (61˚) and uninjured (60˚) which is comparable with other studies (Ikeda, Kurosawa & Kim, 2002; Shirakura et al., 1992 & Tsepis et al., 2004). This finding is replicable in many isokinetic strength testing studies and therefore questions if angle of PT is a somewhat meaningless value with such small differences between limbs in most research. The reliability of using the angle of PT is somewhat debatable as we already know that a PT value can overestimate muscular strength and it does not represent a full torque-angle curve, consequently, the corresponding angle of PT may also lack reliability (Huang et al., 2017). However, Pelegrinelli et al (2018) suggest that understanding the angle of PT allows for clinicians to plan and tailor rehabilitation and training plans towards the late stage of ACLR rehabilitation. Moreover, it was evident that knee flexion angles of <40˚ offered greater deficits, suggesting that PT values may not be the most valuable data for understanding torque-angle strength, however, it should consider that this study only tested ACL deficient patients and not ACLR patients (Eitzen et al, 2010). Hence, providing information based on torque-angle specific windows can identify specific areas to further improve strength before RTS ensuring restoration of knee function throughout the entire RoM.

Current practice still uses PT LSI >90% as RTS criteria, this has implications for more targeted rehab and needs to be addressed in future research to gain a greater knowledge and to further understand and identify limb to limb strength deficiencies. Tengman, Schelin & Hager, (2022) suggest that isokinetic angle-specific torque profiles offer a greater understanding of strength deficits whilst also integrating the torque over time produced which clearly elicits where in the RoM strength deficits occur. Whilst research needs to address future torque-angle analysis to assist in the safe RTS of an athlete after ACLR, it is worth noting that currently there is no evidence from prospective studies which suggests that torque-angle analysis and deficits are linked to ACL injuries or poor outcomes after ACLR. This highlights a novel area of research that needs to continue to be investigated to further understand if this has impact on primary ACL injury as well as the impact it has for RTS after ACLR to mitigate the risk of a contralateral or secondary ACL injury.

2.7 Summary and Thesis Aims

This review of literature has examined ACL anatomy, mechanism, the importance of strength development during rehabilitation following ACLR, and considerations for IKD strength assessment. The limitations outlined require further investigation; including a torque-angle approach as an objective measure to characterise potential deficits in strength following ACLR in athletic populations. It is hypothesized that individuals may often 'pass' RTS assessments using pre-determined thresholds (>90% LSI) when PT is examined. Yet, residual deficits may still be present in specific regions of the torque-angle curve, indicating incomplete recovery of knee function. This research has the potential to highlight isokinetic strength variables that could be used to inform RTS decision-making and guide rehabilitation more clearly after ACLR using more targeted approaches. Therefore, the aims of this thesis are:

1. To provide an overarching description of the angle of PT, H:Q ratios and then LSI at six 10˚ torque-angle windows using an average torque on isokinetic movement of the hamstring and quadriceps. To determine strength profiling for ACLR athletes at concentric and eccentric contractions at 60˚/s at the point of RTS.
2. To investigate if those athletes that 'pass' their RTS assessment using a traditional approach of PT and LSI threshold > 90% value display residual deficits of muscle strength when a more comprehensive strength profile including assessment of the entire torque-angle window is included, when using an average torque value at six interspersed 10º segments rather than PT to provide LSI.
3. To provide a H:Q conventional and functional ratios using a PT value against a H:Q conventional and functional ratios for each of the six 10-degree toque-angle windows using average torque values to provide a comparison.

The hypothesis is that athletes who ‘pass’ the traditional RTS test protocol of ≥ 90% quadriceps PT LSI will still display residual deficits when the torque-angle curve is examined. Hamstring and quadricep muscles at six specified 10° torque-angle windows of knee flexion (20°-29°, 30°-39°, 40°-49°, 50°-59°, 60°-69° and 70°-79°) will highlight that PT values are a misleading value for ‘passing’ RTS criteria compared with a comprehensive strength profiling. These data can identify deficits which would have implications on decision making for the safe RTS of an athlete and would provide data which could determine the progression of rehabilitation after ACLR.

Chapter 3 Methods

3.1 Study Design

This study used retrospective data that had been collected at one single timepoint which was at the time of RTS after ACLR. The study used a retrospective design to examine the effects of ACLR on measures of isokinetic knee extension and flexion torque. The aim was to evaluate if athletes who undergo and complete rehabilitation following ACLR using traditional discharge protocols including the use of pre-determined ‘pass thresholds’ (Quadriceps PT LSI ≥ 90%) (Grindem et al., 2016), to display residual strength deficits when a more comprehensive strength profile including average torque measurements across a 60˚ torque-angle window are examined. Isokinetic strength assessment for quadriceps (CON) and hamstrings (CON and ECC) were performed on both the involved and un-involved limbs at their last assessment date before being discharged to return to RTS after ACLR. For this study, a return to normal team training is how RTS was defined. All IKD strength tests were recorded by a single investigator to ensure internal consistency and avoid inter-tester variability. The test order for all the procedures including time of day were standardised across all final assessments. According to Cohen (1988) to generate a sample size of appropriate power (*d*) which is 80% as level of power for two-tailed hypothesis, $\alpha = .05$, d=1.0, and Power=.80 N=17 (N=34 for between-groups) or (N=17 for within-groups).

3.2 Participants

Twenty-five Qatari male athletes from a range of level 1 sports which all included cutting, planting, pivoting and CoD movements volunteered to take part (Table 1). These sports included basketball (n = 1), soccer (n = 20), futsal (n = 1), handball (n = 1), and volleyball (n = 2).

Table 1. Shows the mean ± SD of player (n=28) anthropometrical characteristics, duration of rehabilitation from surgery to discharge and days/weeks from surgery to last assessment (Ax) date**.**

	Age (Years)	Stature (cm)	Body Mass (kg)	Days Post Surgery of last Rehab Ax	Weeks Post Surgery of last Rehab Ax	Days from Surgery-Discharge	Days from Last Ax to Discharge
Mean	23	176	73	273	39	298	25
SD (±)	4.86	8.88	11.97	101.62	14.52	108.21	34.39

Participants had all sustained primary ACL injury and had to undergo ACLR surgery. All athletes completed a full-time rehabilitation programme (five times per week) at the same Orthopaedic and Sports Medicine Hospital in Qatar before being discharged and RTS at their respective club. Inclusion criteria required athletes to be 18 years of age or over, male, having undergone primary unilateral ACL surgical reconstruction with no concomitant ligamentous knee injuries and competing as a registered player at their respective team within the Qatar Sports Federation before their injury. There was also a requirement to have met a ≥ 90% isokinetic PT value on quadriceps LSI at their final discharge assessment over repetitions 2, 3 and 4 (Figure 2). Two reconstruction autograft fixation methods were used including HS and BPTB performed by two surgeons at the same Orthopaedic & Sports Medicine Hospital.

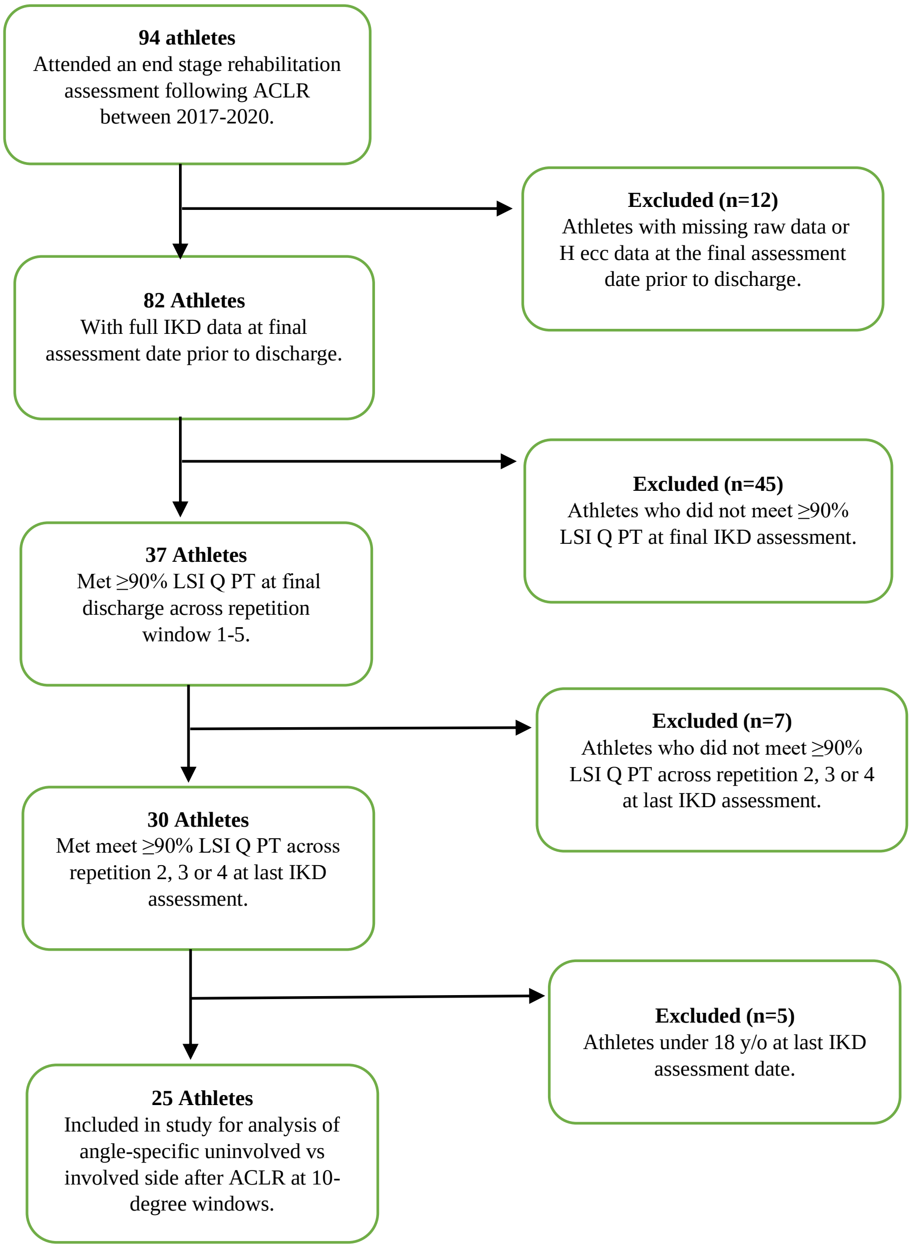

Figure 4. Shows the inclusion criteria for the participants recruited for the study and identifies the participants excluded for not meeting criteria.

All athletes provided informed consent (see appendix 1) prior to the commencement of this study. The study was approved by the institution ethics committee and the Anti-Doping Laboratory Qatar (ADLQ) Institutional Review Board (IRB application number: F2017000227) and the University of Gloucestershire's institutional Research Ethics Committee in accordance with the Declaration of Helsinki (See appendix 2 & 3).

3.1 Procedure

3.3.1 Isokinetic Strength Testing

Athletes were required to perform a standardised warm-up including 5-minutes on a stationary bike (90-100 RPM) (WattBike^{Ltd} Pro- Generation II, Nottingham: England) followed by a series of closed kinetic chain exercises that included bodyweight bilateral and unilateral squats (x 10 reps), step up and downs and a series of countermovement jumps (x 3) and single leg countermovement jumps (x 3 each leg) all of which were part of the rehabilitation process throughout later stages. This made sure that the warm-up protocol could be adhered to easily for all participants without athletes being compromised with new movement patterns. The warm-up incorporated all the major muscle groups in both static and dynamic (explosive) exercises without inducing fatigue, so that the body was prepared for the explosive nature of the Biodex testing. The warm-up procedure was incorporated to stimulate the athletes physically and mentally for testing but also to mitigate the risk of injury when working the athletes knee extensors and flexors under vigorous external forces. Three warm-up trials of isokinetic knee extension/flexion were also performed 60s prior to the commencement of the test as the final aspect of the warm-up prior to the testing protocol. Athletes had previously been familiarized with isokinetic testing procedures as part of routine pre-season and off-season screening for strength testing measures stated by the collaborating institute. This gave the athletes the experience to understand how the testing procedure is conducted and the stress it places on the body from both a physiological and psychological perspective. To enhance their experience of isokinetic testing the Biodex machine was also used to conduct all isokinetic assessments that formed part of routine monitoring during rehabilitation, limiting any learning effect during testing. All the tests conducted were carried out by an experienced physiotherapist/sport scientist who had > 5years experience in isokinetic testing procedures.

A Biodex isokinetic dynamometer (System 4, Biodex Medical Systems, Shirley, New York, USA) was used to record five maximal repetitions of knee extension and flexion respectively on each leg at a test speed of 60˚/s. This low angular velocity ensures a comprehensive RoM is attained at the set velocity (Dvir, 2004 & Kurdak et al., 2005). Whilst testing can vary with higher velocity speeds such as 120˚/s, 180˚/s and 300˚/s isokinetic testing then becomes subject to greater inertial effects at the extremities of the movement (Lepley., 2015 & Undheim et al., 2015). Furthermore, the data captured at these stated isokinetic periods are extremely short due to the acceleration and deceleration requirements, making analysis and interpretation of these data due to the faster speeds, producing greater rep to rep variability than 60˚/s. Athletes were seated on the IKD, with the hip joint at ~85˚ (0˚ = full extension) (Figure 3). The hip in this position allows for the rectus femoris to be engaged fully in knee extension during testing due to it crossing both the knee and hip joint. This means that the testing procedure will highlight any strength deficits within the quadriceps through the full RoM. It is known that the quadriceps act as an antagonist on the ACL and therefore allowing the rectus femoris to be placed under stress from this hip position should detail any deficits. Moreover, previous literature has stated that PT in the quadriceps occurs around 60˚ knee flexion and 80˚ hip flexion (Salzman, Torburn & Perry, 1993). During maximum knee extension the whole quadriceps muscle works simultaneously and not in isolation regardless of the amount of hip flexion (Salzman, Torburn & Perry, 1993), allowing comfort for the athlete whilst still being able to gain the relative data. Continuation of the set-up meant the distal shin pad of the dynamometer was attached proximal to the medial malleolus by using a strap, modified to be subject specific, following the manufacturer's guidelines. Straps were applied across the chest, pelvis, and mid-thigh to restrict accessory and excessive movement from other body parts, (See figure 3) whilst their hands were gripped around the bi-lateral handles. Alignment between the dynamometer rotational axis and the knee joint rotation axis (lateral femoral epicondyle) was checked at the beginning of each trial by the test operator (Grindem et al., 2016; Huang et al., 2017; & Krysitis et al., 2016). Isokinetic assessment included five repetitions of concentric knee flexion and extension followed by five repetitions of eccentric knee flexion. Undheim et al, (2015) review suggest that between three to five repetitions should be collected to analyse data from isokinetic testing based on 24/39 studies utilising this method. Furthermore, extensive literature found that five repetitions be recorded for concentric and eccentric knee extension and flexion testing. This method of recording five repetitions was comparable to other studies who used five repetitions when isokinetic testing at 60˚/s (Baumgart et al., 2018; Crotty et al., 2022; Eitzen et al., 2010; Huang et al., 2017; Pelegrinelli et al., 2018; Welling et al., 2018 & Yosmaoglu et al., 2017). Whilst performing the isokinetic testing (see figure 3) athletes were given consistent and vigorous verbal encouragement of “push and pull” through the complete RoM in English or Arabic based on the athlete’s preference. The uninvolved limb was tested first followed by the involved limb.

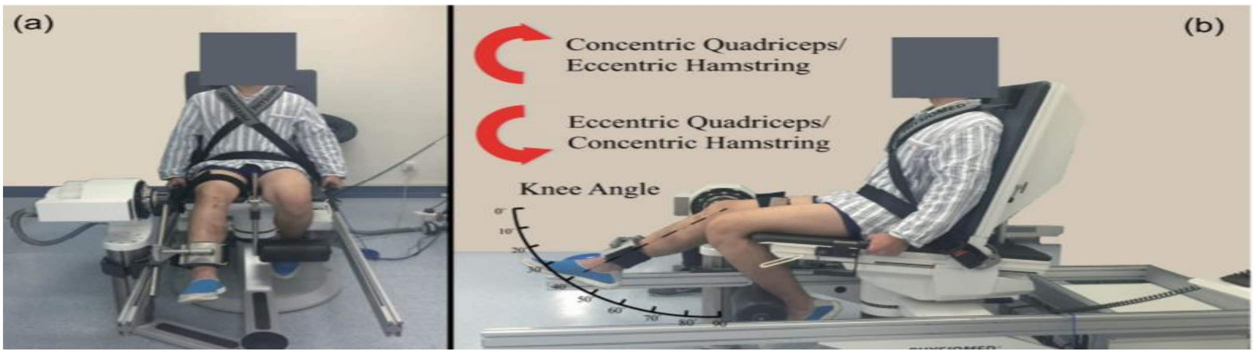

Figure 5. Taken from Huang et al (2017) which shows; (a) an IKD test by an athlete and (b) shows the seated position of the athlete during the range of motion in testing and the contraction of muscles.

3.3.2 Data Extraction

The following variables were extracted and used for analysis: knee extension/flexion PT angles (Nm), and average torque values for specific torque-angle windows as indicated by the lever arm of the dynamometer. H:Q ratios were also recorded and examined at six specific torque-angles in 10˚ segments (20˚-79˚).

The torque-angle profiles were extracted from the original raw torque dataset recorded at 100Hz and transferred into a Microsoft Office Excel 2010 spreadsheet (Microsoft Corporation, Redmond, Washington). Two macro filters were built to extract the relevant data points required for analysis, one from the individual data files for: concentric quadriceps and hamstrings for the right and left leg as well as eccentric hamstrings for the left and right leg. Quadriceps PT values at ≥90% LSI were also extracted to create the inclusion criteria. The second macro filter pulled all twenty-five participants whose quadriceps PT values (≥90% LSI) (inclusion criteria) were achieved over reps 2, 3 and 4 to give data into a final macro-output sheet. The first and last contractions of each rep series were discarded from the analysis (repetitions 1 and 5) this was done due to poor form, inertial effects being present, fatigue and AMI been exhibited in repetitions one and five (Kurdak et al., 2005 & Pua et al, 2008). The remaining three repetitions were used to perform statistical analysis of the 25 athletes. The average torque (Nm) of knee extension and flexion were extracted across all the three recorded trials (2^{nd}, 3^{rd} & 4^{th} repetitions). Along with a single PT value and the corresponding angle from one the three repetitions that produced the greatest torque value. Torque-angle RoM was set from 90-0˚ (Baltzopoulos & Brodie 1989) with six 10˚ degree windows (20˚-29˚, 30˚-39˚, 40˚-49˚, 50˚-59˚, 60˚-69˚ and 70˚-79˚) used for the analysis on knee extension (CON) and flexion (CON/ECC). Torque-angle windows of 10˚ segments were used to base this study on a replication of Eitzen et al (2010) study to investigate six 10˚ angles which was also looked at by Kelis and Katis, (2007). Their study also used Shirakura et al (1992) who looked at 9˚ torque-angle windows between 81˚-9˚ at 60˚/s angular velocity as this allowed the full-strength curve to be analysed without missing any deficits. Angle-specific torque windows provide an appropriate assessment of bilateral strength differences compared to single point angles (Baumgart et al., 2018; Eustace, Page & Greig., 2019). Torque position at the outer RoM from (0˚- 19˚ and 80˚- 90˚) were eliminated from the analyses of the isokinetic curves due to the inertial effects that occur close to the start and end of the movement while accelerating and decelerating (Kurdak et al., 2005; Pua et al., 2008). H:Q ratio were extracted using PT values for conventional and function ratios. However, torque-angle window H:Q ratios were continuously calculated by dividing hamstrings average torque by quadriceps average torque at the same knee angle window (Alhammoud et al., 2019).

Equation 1: H:Q Conventional Ratio

$$= H_{con} / Q_{con}$$

Equation 2: H:Q Functional Ratio

$$= H_{ecc} / Q_{con}$$

3.3 Statistical Analysis

The statistical package SPSS V.27 (IBM Corp) was used to complete the analysis. Descriptive statistics (mean ± SD) were included for Quadriceps concentric, Hamstrings concentric and Hamstrings eccentric for each 10˚ torque angle window. The normality and reliability of the data was assessed using the Shapiro-Wilk test due to the sample size being < 50 (Field, 2013) and by visualisation of the histograms and Q-Q plots. A mixed two-way analysis of variance (ANOVA) was conducted (Field, 2013). Effects were deemed to be statistically significant at a Bonferroni adjusted alpha level of $P < 0.05$. Post hoc analyses was conducted for the results from the mixed two-way ANOVA and where the assumption of sphericity was failed, Greenhouse-Geisser (GG) adjustment was applied (Fields, 2013; Hopkins, 2019). Dependant t-tests were conducted on angle of PT for quadriceps CON and hamstrings CON and ECC with effect sizes using standard published cohens' d thresholds; d= 0.2 small, d = 0.5 medium and large ≥ 0.8 (Field, 2013). Moreover, LSI were calculated for each participant using PT for quadriceps CON LSI for inclusion criteria (figure 1). LSI were then calculated at each of the six 10˚ segments using for all three testing protocols using an average torque value from repetitions 2-4 at each torque-angle window (Involved / Uninvolved*100) expressed as percentage. Descriptive statistics were included for assessing the conventional and functional H:Q ratios as well as conventional and functional H:Q ratios for each of the six 10˚ torque-angle windows.

Chapter 4 Results

Below are the descriptive statistics for the Quadriceps CON (Table 2), Hamstring CON (Table 3) and Hamstring ECC (Table 4). All the tables highlight the two graft types that athletes underwent for ACLR which were HS and BPTB. The tables further highlight the means and standard deviation (±SD) of mean torques for the involved and uninvolved side at each of the six 10-degree torque angle (RoM) windows via graft type and gives a mean value with standard deviation for the total of both graft types. Segment one is 20˚- 29˚, segment two is 30˚- 39˚, segment three is 40˚- 49˚, segment four is 50˚- 59˚, segment five is 60˚- 69˚ and segment six is 70˚-79˚ respectively.

Table 2. Shows the descriptive statistics for the Quadriceps concentric output at 60˚/s for the involved and uninvolved sides for mean torque with means and standard deviation for each of the six 10˚ angle window by graft type.

		Involved Side		Uninvolved Side		
Torque RoM	Graft Type	Mean	± SD	Mean	±SD	Number
20-29˚	HS	74.67	23.29	76.36	33.69	12
	BPTB	98.09	29.44	87.32	20.28	13
	Total	86.85	28.72	82.06	27.52	25
30-39˚	HS	112.17	27.04	112.31	36.12	12
	BPTB	134.06	27.91	121.76	24.30	13
	Total	123.55	29.14	117.22	30.28	25
40-49˚	HS	149.84	30.48	149.32	42.36	12
	BPTB	166.37	30.35	155.45	27.33	13
	Total	158.44	30.94	152.50	34.72	25
50-59˚	HS	183.69	31.13	181.59	43.99	12
	BPTB	191.88	29.81	182.85	33.22	13
	Total	187.95	30.10	182.25	37.93	25
60-69˚	HS	202.70	29.74	199.90	42.46	12
	BPTB	196.45	32.14	198.66	38.30	13
	Total	199.45	30.53	199.26	39.50	25
70-79˚	HS	192.50	30.05	195.55	45.68	12
	BPTB	181.06	37.80	195.24	38.76	13
	Total	186.55	34.09	195.39	41.32	25

Table 3. Shows the descriptive statistics for the Hamstring concentric output at 60˚/s for the involved and uninvolved sides for mean torque with means and standard deviation for each of the six 10˚ angle window by graft type.

		Involved Side		Uninvolved Side		
Torque RoM	Graft Type	Mean	± SD	Mean	±SD	Number
20-29˚	HS	105.86	21.58	115.85	22.01	12
	BPTB	126.39	27.86	124.97	35.86	13
	Total	116.53	26.67	120.59	29.77	25
30-39˚	HS	110.13	19.81	117.30	20.03	12
	BPTB	125.98	25.68	121.13	32.12	13
	Total	118.37	23.98	119.29	26.52	25
40-49˚	HS	104.89	17.29	111.52	19.22	12
	BPTB	120.54	23.37	113.28	28.98	13
	Total	113.02	21.77	112.43	24.29	25
50-59˚	HS	96.97	14.37	103.65	17.86	12
	BPTB	113.23	21.17	105.68	26.09	13
	Total	105.43	19.69	104.71	22.08	25
60-69˚	HS	87.63	12.92	96.14	14.68	12
	BPTB	106.02	19.96	97.54	24.61	13
	Total	97.19	19.07	96.87	20.05	25
70-79˚	HS	75.27	15.12	85.31	13.21	12
	BPTB	94.83	19.62	87.86	22.39	13
	Total	85.44	19.92	86.64	18.23	25

Table 4. Shows the descriptive statistics for the Hamstring eccentric output at 60˚/s for the involved and uninvolved sides for mean torque with means and standard deviation for each of the six 10˚ angle window by graft type.

	Involved Side			Uninvolved Side		
Torque RoM	Graft Type	Mean	± SD	Mean	±SD	Number
20-29˚	HS	158.38	34.70	159.42	44.95	12
	BPTB	166.96	49.81	156.81	40.07	13
	Total	162.84	42.56	158.06	41.60	25
30-39˚	HS	155.01	39.34	161.42	46.81	12
	BPTB	168.71	46.97	157.44	32.53	13
	Total	162.13	43.14	159.35	39.21	25
40-49˚	HS	144.76	39.11	154.71	44.32	12
	BPTB	161.34	43.33	150.81	29.67	13
	Total	153.38	41.37	152.68	36.67	25
50-59˚	HS	131.83	34.97	145.59	38.11	12
	BPTB	150.62	38.36	140.85	28.69	13
	Total	141.60	37.26	143.12	32.91	25
60-69˚	HS	116.32	28.18	132.86	32.65	12
	BPTB	137.13	33.42	129.58	26.79	13
	Total	127.14	32.17	131.16	29.16	25
70-79˚	HS	98.34	21.23	114.98	25.68	12
	BPTB	119.87	28.87	115.40	22.98	13
	Total	109.53	27.28	115.20	23.80	25

The results in table 5 and 6 are indicative of the H:Q conventional and functional ratios. Table 4 highlights the H:Q ratio for the involved and uninvolved side after ACLR using a PT value from the Hamstring CON/Quadriceps CON contractions of repetitions 2-4. Table 4 states there was no significant difference in the conventional (Traditional) ratio and minimal difference (.04) in the FR which also used a PT value from Hamstring eccentric/Quadriceps concentric contractions to provide a ratio. Table 5 below calculated a conventional and FR H:Q ratio but used an average torque value (repetitions 2-4) from the involved and uninvolved side at each 10˚ angle window compared to table 4 which used a PT value. Table 5 highlighted there were no significant increases for involved and uninvolved sides for both conventional and functional H:Q ratios across all torque angle windows. FR of H:Q provided greater ratios at all six torque angle windows for both the involved and uninvolved sides.

Table 5. Shows the H:Q conventional ratio (Hamstrings CON/Quadriceps CON) and H:Q functional ratio (Hamstrings ECC/Quadriceps CON) at 60˚/s IKD testing protocol.

H:Q Conventional Ratio (con/con)		H:Q Functional Ratio (ecc/con)	
Involved side	Uninvolved side	Involved side	Uninvolved side
0.60	0.61	0.84	0.80

Table 6. Shows the H:Q conventional ratio (Hamstrings CON/Quadriceps CON) and H:Q functional ratio (Hamstrings ECC/Quadriceps CON) at 60˚/s IKD testing protocol for each of the six 10˚ torque angle windows using average torque values at each window to produce the H:Q ratios.

	H:Q Conventional Ratio (con/con)		H:Q Functional Ratio (ecc/con)	
Segments	Involved side	Uninvolved side	Involved side	Uninvolved side
20-29˚	1.40	1.50	1.94	1.96
30-39˚	0.98	1.04	1.34	1.37
40-49˚	0.72	0.75	0.99	1.01
50-59˚	0.56	0.58	0.76	0.79
60-69˚	0.49	0.49	0.65	0.66
70-79˚	0.46	0.45	0.60	0.59

Quadriceps CON:

Results from a paired sample *t*-test showed that participants Quadriceps angle of PT for the involved side (65˚± 6.50) was lower than the uninvolved side (68˚ ± 6.09). A paired sample t-test found this difference to be significant, $t(24) = -2.39$, $p < 0.05$, $r = 0.44$. This suggests that the angle of PT of the involved side was significantly lower than the uninvolved side.

Hamstring CON:

Results from a paired sample *t*-test showed that participants Hamstring angle of PT for the involved side (30˚± 12.49) was greater than the uninvolved side (28˚ ± 8.19). A paired sample *t*-test found no significant difference, $t(24) = .920$, $p = .37$, $r = 0.03$. This suggests that the involved side has no significant effect on the angle of PT when compared with the uninvolved side.

Hamstring ECC:

Results from a paired sample *t*-test showed that participants Hamstring angle of PT for the involved side (28˚± 9.37) was lower than the uninvolved side (32˚ ± 9.29). A paired sample *t*-test found this difference to be non-significant, *t*(24) = -1.86, p = .075. This suggests that the involved side has no effect on the angle of PT compared to the uninvolved side. However, it did represent a medium effect size r = 0.35.

Highlighted below (figures; 1, 2 and 3) are the angles of peak torque (PT) and PT value for the involved and uninvolved side for Quadriceps CON, Hamstring CON and Hamstring ECC contractions at an angular velocity of 60˚/s. Each scatter graph has a line of best fit indicated for the involved and uninvolved sides angle of PT.

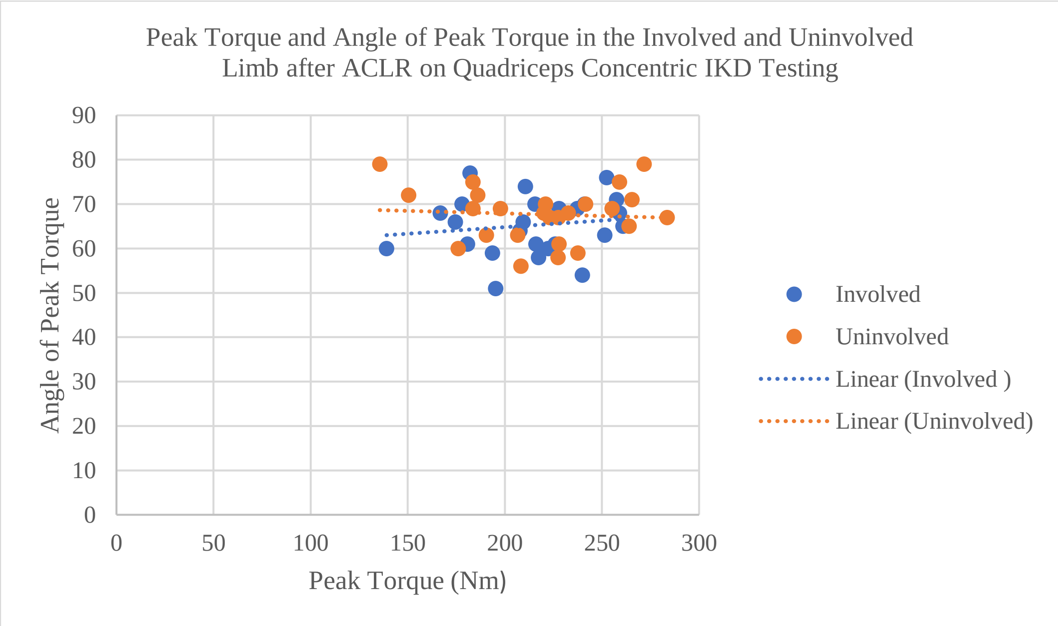

Figure 4. Shows the graph of Quadriceps peak torque (PT) and the angle at which PT occurred for the involved and uninvolved limb during Quadriceps CON contraction during IKD testing.

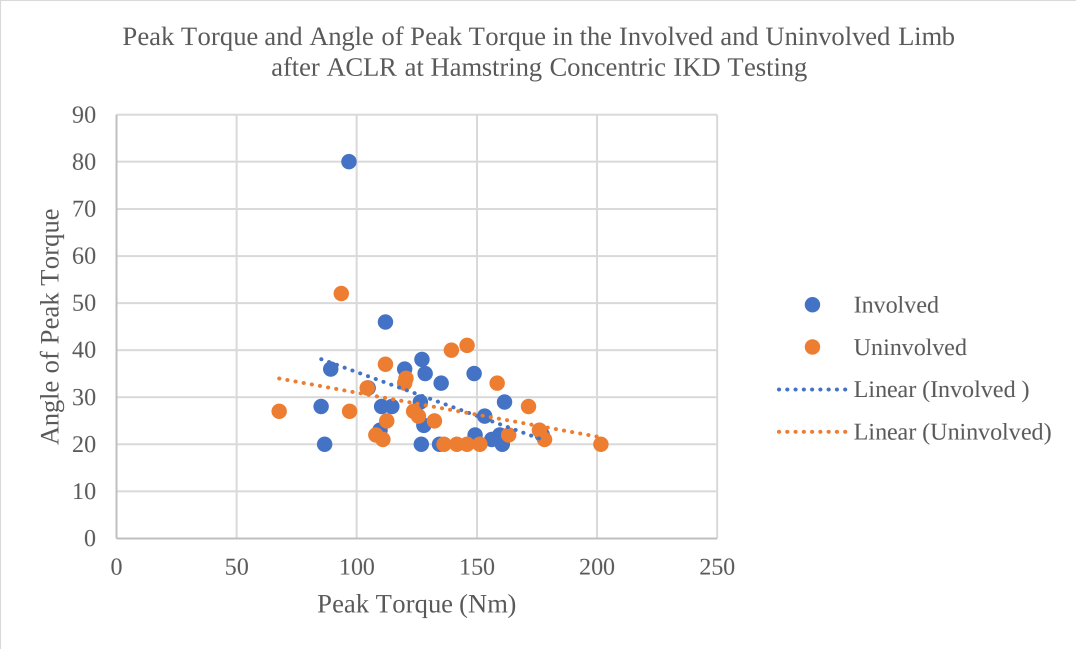

Figure 5. Shows the graph of Hamstring peak torque (PT) and the angle at which PT occurred for the involved and uninvolved limb during Hamstring CON contraction during IKD testing.

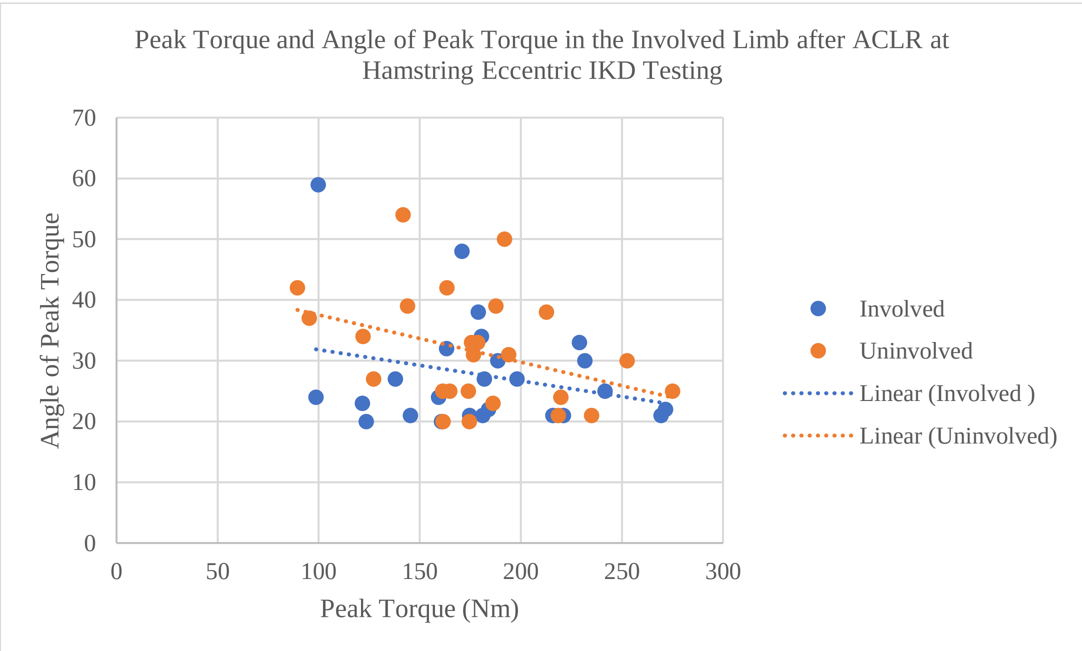

Figure 6. Shows the graph of Hamstring peak torque (PT) and the angle at which PT occurred for the involved and uninvolved limb during Hamstring ECC contraction during IKD testing.

ANOVA Results

When analysing the two-way mixed factoral ANOVA's, no main effect (P>.05) was found for the graft type on average torque for any of the IKD measures (Hamstring CON, Hamstring ECC or Quadriceps CON). The Hamstring concentric assessment however, yielded one main interaction effect (P>.05) between side and graft type F (1, 23) =5.03, r = 0.42. The post hoc test found that the involved side had greater average torque scores for the BPTB graft rising from a mean of 108.40Nm on the uninvolved leg (not significantly different) to 114.50Nm which was significantly different (F (1,23) =5.77, P=.025, r = 0.45) to the involved side starting at 104.96Nm falling to 96.79Nm.

The one significant main effect was found in the 10˚ segment variable found in all three measures: Hamstring CON F (1.76, 115) =51.47, P<.001, r = 0.83, Hamstring ECC F (1.46, 33.65) =67.11 P<.001, r = 0.57 and Quadriceps CON F (5, 115) =173.51 P<.001, r = 0.63. Both hamstring measures resulted in the same results when examining the post hoc analysis. Both the Hamstring CON (F (5, 19) =18.85, P<.001, r = 0.71) and Hamstring ECC (F (5, 19) =29.01, P<.05, r = 0.63) interactions showed that segments decreased in average torque as the angle of the 10˚ segment window increased. Significant differences (p<.05) were found for all segments interactions apart from segments 1 & 2 and 1 & 3. The post hoc test for Quadriceps CON found a different significant interaction (F (5, 19) =92.17 P<.001, r = 0.41). The results showed that segments increased in average torque as the angle of the 10˚ segment window increased. The segments were significantly different (p<.05) apart from segments 4 & 6 and 5 & 6. This is because average torque for segment 6 (70˚- 79˚) dropped below the average torque for segment 5 (60˚- 69˚).

Limb Symmetry Index for Hamstring Concentric, Eccentric and Quadriceps Concentric

The results below (Tables; 7, 8 and 9) show all 25 athletes who have been RTS based on their quadricep PT value of ≥90 % LSI (Grindem et al., 2016) which is also highlighted in the table next to each participant. The three tables endeavour to provide a visual representation of each athlete across the six 10˚ windows to highlight where deficits are occurring across the RoM at the angular velocity 60˚/s for quadriceps CON, hamstring CON and hamstring ECC muscle contractions on the IKD at the point of RTS isokinetic strength testing. The three tables (6, 7 and 8) are highlighted in three different colours to represent a traffic light system for (≥ 90% LSI [green], 80-89 % LSI [amber] and ≤ 80% LSI [red]) average torque LSI % (involved/uninvolved side *100) at each 10˚ segment. Those participants that exceed the ≥90% cut-off when viewed in 10˚ segments are in green, this matches the high RTS standards of the University of Delaware return-to-sport criteria (Adams et al. 2012; Barber-Westin & Noyes 2011). The orange indicates those that are between an 80-90% threshold, anything above 80% is commonly used as a RTS marker (Adams et al., 2012 & Barber-Westin & Noyes 2011; Wellsandt et al., 2017), whilst the red indicates those below 80% threshold of their involved side vs uninvolved side. The results provide a visual comparison of the athletes who were achieving ≥ 90% LSI at quadriceps PT and the ability to maintain the ≥ 90% LSI using average torque through the full RoM. Each table (7, 8 and 9) has a solid black line which is referring to and delineating the ≥ 90% LSI 'cut-off' that is referred to in current literature to 'pass' and 'safely' RTS after assessment batteries. The athletes are ranked based on the lowest value to highest value in the RoM (i.e., participant 15 had 47% LSI in 20˚- 29˚ segment of quadricep CON, the second lowest ranked was participant 16 who had 65% LSI in 70˚- 79˚ segment at hamstring CON followed by participant 17 who was the third lowest ranked and had 68% LSI in 20˚- 29˚ segment of hamstring ECC). The three tables (7,8 and 9) show each athlete performing the three isokinetic muscle testing procedures. Table 7 highlights a full representation of all three contractions together for each athlete, so it is visible to see a comparison across all three tests in one table. While table 8 highlights the athletes who had a BPTB graft and has them in ascending order of average torque LSI %. Table 9 follows the same principle and has the athletes highlighted who had a HS graft with them in ascending order of average torque LSI %.

Table 7. Shows the Quadriceps peak torque LSI % (≥90) for each athlete and the mean torque between the involved and uninvolved side across each 10˚ window for the Quadriceps concentric, Hamstring concentric and Hamstring eccentric contractions across a torque window of 20-79 degrees. Highlighting if athletes have 'safely passed' ≥90% LSI across each window in comparison to Quadriceps PT ≥90% LSI pass criteria.

Quadriceps PT LSI % and LSI % for each 10 Degree Windows inference of the Involved side vs Uninvolved side (Involved / Uninvolved x100) for mean torque on Quadriceps concentric, Hamstring concentric and eccentric																			
		Quadriceps Concentric LSI %						Hamstrings Concentric LSI %						Hamstring Eccentric LSI %					
Participant	Q PT LSI%	20-29˚	30-39˚	40-49˚	50-59˚	60-69˚	70-79˚	20-29˚	30-39˚	40-49˚	50-59˚	60-69˚	70-79˚	20-29˚	30-39˚	40-49˚	50-59˚	60-69˚	70-79˚
P15	99	47	87	90	103	100	92	83	100	101	102	105	93	79	84	87	93	89	87
P16	99	133	135	135	125	121	99	86	85	89	89	81	65	121	95	83	75	78	74
P17	92	70	72	76	84	90	93	113	119	113	104	91	91	68	70	70	70	77	80
P23	91	104	103	102	97	91	86	84	81	83	85	77	68	104	103	99	98	94	92
P19	95	95	92	94	97	118	183	85	88	92	94	98	98	93	88	84	82	73	69
P22	95	82	89	92	93	99	93	89	89	87	84	77	69	95	93	94	82	73	69
P10	95	101	108	102	100	98	98	70	76	82	91	101	115	83	91	96	102	108	110
P25	91	81	92	96	93	87	74	91	86	81	81	80	76	99	92	86	82	76	75
P6	92	76	84	85	90	94	94	104	105	103	100	97	86	125	119	111	105	105	107
P8	92	114	113	110	103	92	77	103	102	104	101	96	91	99	99	100	103	107	110
P11	111	114	138	145	141	123	107	78	91	94	96	98	99	97	97	97	95	94	91
P20	97	79	84	92	96	97	97	90	97	102	103	104	104	105	120	130	136	136	130
P14	108	92	102	106	110	108	111	80	92	95	95	95	92	110	106	104	98	92	87
P24	115	107	107	116	115	102	82	87	83	82	82	88	99	97	100	102	103	101	99
P7	90	96	95	96	96	93	94	82	84	91	92	92	96	91	88	91	88	88	88
P1	98	90	84	87	93	96	96	93	96	101	102	101	104	89	90	90	93	94	96
P5	98	336	165	138	121	104	85	96	100	96	95	99	105	121	117	113	110	99	92
P18	94	129	115	103	96	91	90	110	106	109	110	108	100	103	98	95	96	96	86
P12	93	130	111	92	91	93	97	95	98	97	95	94	94	107	101	100	98	96	95
P21	99	123	123	119	114	103	92	130	142	151	153	144	127	119	121	120	121	122	128
P2	98	114	110	103	96	93	97	118	113	107	107	113	122	131	121	114	108	104	101
P9	111	111	104	112	121	113	98	95	98	101	107	116	123	135	128	119	109	103	99
P3	103	158	146	135	128	114	97	130	126	129	128	128	125	104	108	111	115	116	111
P4	95	174	148	134	121	109	97	199	190	188	175	172	149	131	122	115	111	107	104
P13	113	134	116	105	106	108	113	100	98	100	107	108	113	102	101	101	100	103	105

***Q PT LSI % - Quadriceps Peak Torque Limb Symmetry Index %**

****Solid black line denotes a cut off value of ≥90% LSI of Quadriceps Peak Torque which highlights athletes below the line who safely RTS using the ≥90% LSI cut-off.**

(green)	=≥90% LSI
(orange)	= 80-89% LSI
(red)	= <80% LSI

Table 8. Shows athletes who have undergone ACLR and had a BPTB graft. Quadriceps peak torque LSI % (≥90) for each athlete and the mean torque between the involved and uninvolved side across each 10˚ window for the Quadriceps concentric, Hamstring concentric and Hamstring eccentric contractions across a torque window of 20˚- 79˚. Highlighting if athletes have ‘safely passed’ ≥90% LSI across each window.

BTB Graft Types LSI % for each 10 Degree segment for mean torque on Quadriceps concentric, Hamstring concentric and eccentric																			
		Quadriceps Concentric LSI %						Hamstrings Concentric LSI %						Hamstring Eccentric LSI %					
Participant	**Q PT LSI%**	**20-29˚**	**30-39˚**	**40-49˚**	**50-59˚**	**60-69˚**	**70-79˚**	**20-29˚**	**30-39˚**	**40-49˚**	**50-59˚**	**60-69˚**	**70-79˚**	**20-29˚**	**30-39˚**	**40-49˚**	**50-59˚**	**60-69˚**	**70-79˚**
P15	**99**	47	87	90	103	100	92	83	100	101	102	105	93	79	84	87	93	89	87
P10	**95**	101	108	102	100	98	98	70	76	82	91	101	115	83	91	96	102	108	110
P8	**92**	114	113	110	103	92	77	103	102	104	101	96	91	99	99	100	103	107	110
P20	**97**	79	84	92	96	97	97	90	97	102	103	104	104	105	120	130	136	136	130
P24	**115**	107	107	116	115	102	82	87	83	82	82	88	99	97	100	102	103	101	99
P7	**90**	96	95	96	96	93	94	82	84	91	92	92	96	91	88	91	88	88	88
P18	**94**	129	115	103	96	91	90	110	106	109	110	108	100	103	98	95	96	96	86
P12	**93**	130	111	92	91	93	97	95	98	97	95	94	94	107	101	100	98	96	95
P21	**99**	123	123	119	114	103	92	130	142	151	153	144	127	119	121	120	121	122	128
P2	**98**	114	110	103	96	93	97	118	113	107	107	113	122	131	121	114	108	104	101
P9	**111**	111	104	112	121	113	98	95	98	101	107	116	123	135	128	119	109	103	99
P3	**103**	158	146	135	128	114	97	130	126	129	128	128	125	104	108	111	115	116	111
P4	**95**	174	148	134	121	109	97	199	190	188	175	172	149	131	122	115	111	107	104

Table 9. Shows athletes who have undergone ACLR and had a HS graft. Quadriceps peak torque LSI % (≥90) for each athlete and the mean torque between the involved and uninvolved side across each 10˚ window for the Quadriceps concentric, Hamstring concentric and Hamstring eccentric contractions across a torque window of 20˚- 79˚. Highlighting if athletes passed ≥ 90%.

HS Graft Types LSI % for each 10 Degree segment for mean torque on Quadriceps concentric, Hamstring concentric and eccentric																			
		Quadriceps Concentric LSI %						Hamstrings Concentric LSI %						Hamstring Eccentric LSI %					
Participant	**Q PT LSI%**	**20-29˚**	**30-39˚**	**40-49˚**	**50-59˚**	**60-69˚**	**70-79˚**	**20-29˚**	**30-39˚**	**40-49˚**	**50-59˚**	**60-69˚**	**70-79˚**	**20-29˚**	**30-39˚**	**40-49˚**	**50-59˚**	**60-69˚**	**70-79˚**
P16	**99**	133	135	135	125	121	99	86	85	89	89	81	65	121	95	83	75	78	74
P17	**92**	70	72	76	84	90	93	113	119	113	104	91	91	68	70	70	70	77	80
P23	**91**	104	103	102	97	91	86	84	81	83	85	77	68	104	103	99	98	94	92
P19	**95**	95	92	94	97	118	183	85	88	92	94	98	98	93	88	84	82	73	69
P22	**95**	82	89	92	93	99	93	89	89	87	84	77	69	95	93	94	82	73	69
P25	**91**	81	92	96	93	87	74	91	86	81	81	80	76	99	92	86	82	76	75
P6	**92**	76	84	85	90	94	94	104	105	103	100	97	86	125	119	111	105	105	107
P11	**111**	114	138	145	141	123	107	78	91	94	96	98	99	97	97	97	95	94	91
P14	**108**	92	102	106	110	108	111	80	92	95	95	95	92	110	106	104	98	92	87
P1	**98**	90	84	87	93	96	96	93	96	101	102	101	104	89	90	90	93	94	96
P5	**98**	336	165	138	121	104	85	96	100	96	95	99	105	121	117	113	110	99	92
P13	**113**	134	116	105	106	108	113	100	98	100	107	108	113	102	101	101	100	103	105

Table 7 above illustrates the results of each participant across all three testing protocols: quadriceps CON, hamstrings CON and hamstrings ECC at an angular velocity of 60˚/s. The results allow for each participant to be visualised and compared against one another across all six 10˚ segments at all three individual tests. The results show that only 28% (7/25) participants achieved a ≥ 90% mean torque LSI across all six 10˚ segments at all three testing protocols. While 16% (4/25) achieved ≥ 90% mean torque LSI across all six 10˚ segments except for in only one window. From the 72% (18/25) participants who did not achieve ≥ 90% mean torque LSI across all six 10˚ segments, 78% (14/18) elicited two or more segments that achieved ≤90% mean torque LSI across all six 10˚ segments at quadriceps CON, hamstring CON and hamstring ECC isokinetic testing contractions.

Quadriceps CON

In table 7 below it is evident that whilst all participants (25) pass the Quadriceps PT ≥ 90% LSI, only 56% (14/25) participants managed to have a ≥ 90% LSI mean torque across all six 10˚ torque angle segments. Furthermore, of the 44% (11/25) who did not achieve ≥90% LSI mean torque across the 10˚ angle torque segments evidence that 64% (7/11) participants had two or more 10˚ torque angle segments that achieved ≤ 90% LSI. The results highlight that 55% (6/11) participants also had at least one 10˚ torque angle segment that achieved ≤80% LSI. Of the 11 participants who did not achieve ≥ 90% LSI mean torque had large LSI deficits at 20˚- 29˚ 55% (6/11) and 30˚- 39˚ 55% (6/11) respectively. It should be noted that only 2/25 participants achieved ≤ 90% LSI mean torque at windows 50˚- 59˚ and 60˚- 69˚ which is where PT of quadriceps is found in literature. Finally of the 44% (11/25) who did not pass ≥ 90% LSI mean torque across all six 10˚ torque angle windows, 45% (5/11) had a deficit of ≤ 90% LSI at 70˚- 79˚ with 40% (2/5) participants having a mean torque LSI at ≤80% LSI.

Hamstring CON

The results in table 7 above show that whilst all participants (25) pass the Quadriceps PT ≥ 90% LSI, only 52% (13/25) participants managed to have a ≥ 90% LSI mean torque across all six 10˚ torque angle segments in hamstring CON testing. Furthermore, 48% (12/25) did not achieve ≥90% LSI average torque across the 10˚ torque-angle segments for hamstring CON contractions in IKD testing. Moreover, it evidences that of the 48% participants who did not achieve a ≥ 90% LSI mean torque across all six 10˚ segments, 75% (8/12) participants had two or more 10˚ torque-angle segments that achieved ≤ 90% LSI. The results also highlight that 42% (5/12) participants also had at least one 10˚ torque angle segment that achieved ≤80% LSI. Of the 48% of participants who did not achieve ≥ 90% LSI mean torque at all segments, 42% (5/12), had five 60% (3/5) or even all six 40% (2/5) torque-angle windows at a threshold of ≤ 90% LSI mean torque at hamstring CON contractions. LSI deficits appeared across the full RoM in the 48% that failed to achieve ≥ 90% LSI mean torque. These deficits occurred at 20˚- 29˚ (9/12), 30˚- 39˚ (8/12), 40˚- 49˚ (6/12), 50˚- 59˚, 60˚- 69˚ and 70˚-79˚ segments all had 5/12 participants achieve ≤ 90% LSI mean torque at each respective angle window. It should be noted that 4/5 participants who did not achieve ≥ 90% LSI mean torque at window 70-79˚ achieved ≤80% LSI mean torque.

Hamstring ECC

The results in table 7 above show that whilst all participants (25) pass the Quadriceps PT ≥ 90% LSI, only 56% (14/25) participants managed to have a ≥ 90% LSI mean torque across all six 10˚ torque-angle segments in hamstring ECC testing. Furthermore, 44% (11/25) did not achieve ≥90% LSI mean torque across the six 10˚ torque-angle segments for hamstring ECC contractions in IKD testing. Moreover, of the 44% of participants who did not achieve a ≥ 90% LSI mean torque across all six 10˚ segments, 64% (7/11) participants had two or more 10˚ torque-angle segments that achieved ≤ 90% LSI. The results also highlight that 55% (6/11) participants also had at least one 10˚ torque-angle segment that achieved ≤80% LSI. Results show of the 44% of participants who did not achieve ≥ 90% LSI mean torque at all segments, 55% (6/11), had five 60% (3/5) or even all six 40% (2/5) torque-angle windows at a threshold of ≤ 90% LSI average torque at hamstring CON contractions. LSI deficits appeared across the full RoM in the 44% that failed to achieve ≥ 90% LSI mean torque. These deficits occurred in participants at segments; 20˚- 29˚ (4/11), 30˚- 39˚ (4/11), 40˚- 49˚ (5/11), 50˚- 59˚ (6/11), 60˚- 69˚ (7/11) and 70˚-79˚ (9/11). Results show that 5/7 participants achieved ≤80% LSI mean torque at 60˚- 69˚ segment and 4/9 participants achieved ≤80% LSI mean torque at 70˚-79˚ segment respectively.

Separation by Graft Types

Main findings for results in table 8 and 9 highlight all 25 athletes by graft type: for BPTB (table 7) and HS (table 8). Table 7 illustrates that of the 13 athletes 46% (6/13) who underwent a BPTB graft for ACLR achieved average torque ≥ 90% LSI across all six 10˚ windows over all three isokinetic testing procedures at the point of RTS. Whereas only 8% (1/12) of athletes who underwent a HS graft for ACLR achieved average torque ≥ 90% LSI across all six 10˚ windows over all three isokinetic testing procedures at the point of RTS. Generally, the majority of residual limb symmetry deficits were found in hamstring CON and ECC isokinetic testing procedures for athletes who had undergone BPTB and HS grafts for ACLR.

Chapter 5 Discussion

5.1 General Discussion

The overall purpose of this thesis was to examine isokinetic strength in soccer and other pivoting athletes using the traditional methods, including peak torque and LSI thresholds. In addition to the traditional methods of assessment, a strength profile was formulated which considers torque production across the full RoM tested. The use of strength profiling is proposed to provide a greater depth of analysis across specific torque-angle windows which may have potential implications for RTS decision-making, and subsequently, late-stage rehabilitation.

Therefore, an important and novel aspect of this thesis was to utilise a consistent approach to provide an overarching isokinetic strength profile of athletes after ACLR. The primary findings of this thesis offer an insight to a detailed approach to RTS isokinetic testing for athletes following ACLR. Utilising this approach instead of the traditional method for isokinetic testing for RTS (PT value and LSI > 90% of the uninvolved limb) yields greater insights compared to PT which has almost been used as a 'one size fits all' approach in the past to RTS for athletes undergoing ACLR. Consequently, the use of this data has more than likely, in a lot of cases, caused clinicians to inadequately guide athletes to RTS in a de-conditioned state due to residual knee extensor and flexor deficits from misleading PT data (Wellsandt et al., 2017). Subsequently, increasing the risk of future re-injury or potential contralateral ACL injury (Grindem et al., 2016; Kyritsis et al., 2016; Webster & Hewett, 2019). Therefore, this novel approach of assessing torque production across a full RoM using average torque at each 10˚ torque-angle window to calculate LSI % and H:Q ratios will offer profiling that practitioners can apply practically in rehabilitation. This method of strength profiling across the full torque-angle curve will look to appropriately assess an athletes knee extensor and flexor muscular strength with the ability of appropriately characterizing and understanding the 'bigger picture' of an athletes strength profile, where in the past a PT value has been classified as sufficient knowledge required for RTS, but may now be deemed as tenuous due to only looking at one single timepoint to determine an outcome to 'safely' RTS for athletes.

This discussion chapter intends to synthesise the findings from the retrospective data within the thesis in relation to the stated aims and hypothesis, whilst highlighting how and where the aims have been achieved. Each aim will be discussed consecutively for clarity, with findings discussed and critiqued in conjunction with existent literature to highlight the addition that this MSc thesis contributes to the extant body of research. The limitations of the thesis will be outlined and explained to help with practical application for clinicians and future research. It is anticipated that following this section of the thesis, practitioners will be able to start to question the use of a single

PT value. Thus, providing practitioners with an idea of why it is useful to utilise a wealth of data around a strength profile and how it provides a more detailed approach of torque-angle analysis for RTS after ACLR, it is hoped that clinicians can integrate the findings of this thesis into their clinical practice to enhance the strength profile in RTS. For clarity, the thesis aims, and hypothesis are stated below:

5.2 Thesis Aims

1. To provide an overarching description of the angle of PT, H:Q ratios and then LSI at six 10˚ torque-angle windows using an average torque on isokinetic movement of the hamstring and quadriceps. To determine strength profiling for ACLR athletes at concentric and eccentric contractions at 60˚/s at the point of RTS.
2. To investigate if those athletes that 'pass' their RTS assessment using a traditional approach of PT and LSI threshold > 90% value display residual deficits of muscle strength when a more comprehensive strength profile including assessment of the entire torque-angle window is included, when using an average torque value at six interspersed 10˚ segments rather than PT to provide LSI.
3. To provide a H:Q conventional and functional ratios using a PT value against a H:Q conventional and functional ratios for each of the six 10˚ toque-angle windows using average torque values to provide a comparison.

5.3 Thesis Hypothesis

The hypothesis is that athletes who 'pass' the traditional RTS test protocol of ≥ 90% quadriceps PT LSI will still display residual deficits when the torque-angle curve is examined. Hamstring and quadricep muscles at six specified 10˚ torque-angle windows of knee flexion (20˚-29˚, 30˚-39˚, 40˚-49˚, 50˚-59˚, 60˚-69˚ and 70˚-79˚) will highlight that PT values are a misleading value for 'passing' RTS criteria compared with comprehensive strength profiling. These data points can identify deficits which would have implications on decision-making for the safe RTS of an athlete and could provide data which could determine the progression of rehabilitation after ACLR.

5.4 Discussion Specific Findings

The thesis evaluated torque production at six 10˚ torque-angle windows (20˚- 79˚ knee flexion RoM) for hamstring and quadriceps function at the point of RTS after ACLR. Our hypothesis was supported by the results established from the torque-angle windows using an average torque to gain an insight of limb symmetry between the involved and uninvolved limb post ACLR at the time of RTS. It elicited that ACLR athletes reveal residual LSI deficits particularly in the outer RoM (20˚-29˚, 30˚-39˚ and 70˚-79˚) for quadriceps CON contraction. Moreover, similar characteristics were found in the hamstring CON contraction whereby LSI % at angles of 20˚- 49˚ exhibited the majority of poor limb symmetry; however, it must be noted that those athletes who struggled with meeting > 90% LSI in the first three segment windows also produced lower LSI scores across the full RoM analysed. In conjunction with these results the hamstring ECC data provided a greater indication that those who suffer with residual strength deficits in the hamstring CON have increasingly lower LSI % across an ECC hamstring contraction too. This vital piece of information is a concern when we look back at potential MOI for ACL injury which has been previously highlighted in movements that include rapid acceleration, deceleration and pressing movements (Della Villa et al., 2020). We already know that in these situations hamstring eccentric contractions are occurring and thus lengthening the muscle while the force applied to the muscle exceeds the force produced by the muscle itself (Lindstedt et al., 2001). Therefore, if the hamstring muscles cannot withstand the momentary force applied in this mode of contraction it automatically increases the physiological stress on co-activating muscles and surrounding structures such as the ACL (Osternig., 2000; Ward et al., 2015).

Therefore, we need to imply statistically how and why this may contribute to enhancing LSI % and further understanding the strength profile of athletes at the point of RTS after ACLR. This study, however, used statistical analysis to suggest that there was tenuous links between the involved and uninvolved side on torque production at each 10˚ window of analysis, but it did not suggest that graft type had any significant effect on the torque-angle analysis. From the interpretation of previous literature, we know that PT values have been construed to be the most useful piece of information to 'pass' a criterion for RTS (Grinderm et al., 2016; Kryritsis et al., 2016). From the analysis provided we know that PT occurred in quadriceps CON contractions at 65˚± 6.50˚ for the involved side compared to the uninvolved side (68˚ ± 6.09˚) which is in line with similar findings from Read et al., (2021). Eitzen et al., (2010) also found extensor PT occurred at 61˚ and 60˚ for the involved and uninvolved side respectively, although these were ACL deficient patients, concurring with previous findings (Ikeda, Kurosawa & Kim., 2002; Shirakura, Kato & Udagawa., 1992; Slocker de Arce et al., 2001; Tsepis et al., 2004). The paired sample *t*-test found the difference to be significant, $t(24) = -2.388$, $p < 0.05$, $r = 0.44$ suggesting that the angle of PT of the involved side was significantly lower than the uninvolved side with a medium effect size proving the relationship. As expected, the descriptive statistics for quadriceps CON (table 1) highlight the mean torque values with the highest mean values on the involved and uninvolved side coming in the 60˚- 69˚ torque-angle window. The post hoc test for quadriceps CON found a different significant interaction ($F(5, 19) = 92.17$ $P < .001$, $r = 0.41$) which exhibits a medium effect size (Cohens, 1998). It is worth noting that these results showed that each of the six 10˚ segments increased in average torque as the angle of the 10˚ segment window increased (0˚/180˚= full leg extension [see figure 2 & 3]; Eitzen et al., 2010; Huang et al., 2017), offering a parabola curve on the torque production, and highlighting what we would want to see in a rehab perspective. The segments were significantly different ($p<.05$) apart from segments 4 (50˚- 59˚) and 6 (70˚- 79˚), and segment 5 (60˚- 69˚) and 6 (70˚- 79˚). This was because average torque for segment 6 dropped below the average torque for segment 5. The descriptive results also show that athletes who have had BPTB graft (n=13) tend to elicit greater average torques in the involved side than the uninvolved side apart from the outer RoM (70˚- 79˚) where the uninvolved side proved to have 14Nm greater force production. The descriptive statistics from table 1 also highlight that generally those who had BPTB grafts compared with HS grafts (n=12) attained greater force production throughout the RoM for involved and uninvolved sides for knee extension except in torque-angle windows 60˚- 69˚ and 70˚- 79˚ where those who had HS grafts provided greater force production which could imply that where PT occurs, does not necessarily warrant the most relevant outcomes for quadriceps strength profile in those with ACLR. Rate of force production would be another variable to consider assessing in future investigations. As mentioned previously if mechanoreceptors of the ACL are inhibited this can lead to neuromuscular dysfunction. Poor neuromuscular function can lead to a lower level of hamstring and quadriceps strength meaning a deficit in certain angle-specific windows (Read et al., 2021). Therefore, it is imperative that future studies should consider identifying the rate of torque production pre and post ACLR. Conversely, it should be attenuated that it is clear to see from the descriptive statistics (table 1), there was a linear approach to average torque across all RoM 20˚- 79˚, but it should be noted that the uninvolved side was at a reduced average torque across all torque-angle windows except 70˚- 79˚ collectively (BPTB and HS grafts n=25). This could in part be due to the under-conditioned loading that the uninvolved side has gone through and the potential stress that has led to deconditioning whilst recovering from ACLR. Also highlighting why it may not be enough to just use the uninvolved limb as a reference marker during limb symmetry equations for RTS but pre-injury (EPIC) values where available (Wellsandt et al., 2017).

Furthermore, dependant *t*-test results provided for the hamstring concentric and eccentric contractions show that PT occurred at 30˚ for the involved side and 28˚ for the uninvolved side and then 28˚ for the involved side and 32˚ for the uninvolved side respectively which is similar findings from Read et al., (2021). The post hoc test for hamstring CON found that the involved leg had higher average torque scores for BPTB grafts rising from a mean of 108.4Nm on the uninvolved side (not significantly different) to 114.5Nm which was significantly different ($F(1,23) = 5.77$, $P=.025$, $r=0.45$) to the involved side for HS graft which started at 104.96Nm to 96.79Nm. Average torque across all six torque-angle windows yielded greater results for those with HS grafts in the uninvolved side compared with BPTB grafts who had greater torque production scores on the involved side (table 2). This in fact could be due to the rehabilitation process the BPTB athletes had been through in the early stages of rehabilitation when more hamstring focussed exercises can be addressed compared with those who have had a HS graft and donor site morbidity can occur as well as altered neural and morphological characteristic changes (Lepley et al., 2019). It was a similar pattern followed in the hamstring ECC testing whereby athletes who had undergone BPTB grafts produced higher average torques across all six 10˚ windows of knee flexion on the involved side compared with the uninvolved side. Those with HS grafts produced greater average torque across all six torque-angle windows on the uninvolved side compared to the involved side (table 3). Both the hamstring CON (F (5, 19) =18.85, $P<.001$, $r = 0.71$) and hamstring ECC (F (5, 19) =29.01, $P<.05$, $r = 0.63$) interactions showed that segments decreased in average torque as the angle of the 10˚ segment window increased with large effect sizes (Cohen., 1992). Significant differences ($p<.05$) were found for all segments interactions apart from segments 1 & 2 and 1 & 3. Whilst statistical analysis did not yield a huge array of statistical significance on graft type; future analysis could be undertaken with a larger cohort (>50) of ACLR patients which may unearth greater statistical significance between graft types and average torque compared to no main effect ($P>.05$) found for the graft type on average torque for any of the IKD measures in this study.

Interestingly, regardless of graft type (BPTB or HS) the athletes generally showed a lower level of muscular strength in the hamstrings. Moreover, those athletes showed lower average and PT scores produced across the torque-angle windows in both hamstring contractions (CON & ECC). Previous research has demonstrated that HS grafts offer a greater reduction in force production at the donor site (Cohen et al., 2014; Read et al., 2021). Ultimately, this information needs to be decimated to clinicians and surgeons because it needs to be considering when sharing the decision-making process for future ACLR patients. Information around graft types has long been debated and will continue to be in the future. Research such as this helps to make logical decisions around aspects of rehabilitation that can be nurtured to minimise deficits in specific torque-angle windows and modes of contractions. Whilst we understand that HS grafts mean no isolation work can start until 6/52 post-surgery, we also know that hamstring strength in both CON/ECC contractions is notably reduced over time after ACLR. Reinforcement of both CON and ECC contractions of the hamstrings must be applied during rehabilitation to enhance RFD and ground reaction forces (Read et al., 2021). Failure to apply these types of contractions within the rehabilitation protocol increases the risk of ACL re-injury and repetitive strain injury to the hamstrings as they will not be able to cope with the force produced in certain accelerating and decelerating tasks. Understanding the principal theories of agonist/antagonist muscles is imperative for clinicians during the rehabilitation process. Whilst we have defined why it is a necessity to have strong hamstrings the same occurs for the quadriceps (Kyritsis et al., 2016). For optimal function of the knee and to reduce the loading capacity on the ACL the quadriceps also must become extremely robust in CON and ECC contractions, without this the coactivation between the hamstrings and quadricep muscles risk increasing the odds of secondary ACL injury. Establishing these principals influences how a clinician can logically build a rehabilitation plan with the athlete to make sure strength deficits are minimised at the point of RTS. Equally, understanding this type of information allows the clinician to build a rapport with their athletes, resulting in, 'buy-in' from the athlete because they feel reassured from the education they have received from the clinician and thus feel informed and part of the decision-making process in the post-surgery rehabilitation (Forsdyke et al., 2016; Persson et al., 2022).

5.5 Limb Symmetry Findings

Recent literature has provided a growing body of evidence that torque-angle analysis should be conducted across a full RoM compared to just using a PT value to conduct limb symmetry on knee extensors and flexors during isokinetic RTS testing (Read et al., 2021; Hart et al., 2022). These studies have recently used statistical parametric mapping (SPM) to highlight residual deficits throughout a RoM. Over a three timepoint period it was found that residual deficits went from 28˚- 81˚, 32˚- 81˚, and 51˚- 80˚ at the first, second and third timepoint respectively in knee extension (Read et al., 2022). These findings highlight one area of concern this study aimed to assess, which is, are those who meet current recommended RTS criteria (> 90% PT LSI) as per Grindem et al (2016) still producing residual strength deficits due to altered knee function which subsequently increases the risk of re-rupture. Because of ACL injury and ACLR we know that performance and knee function can be altered and provide long lasting deficits (Noll et al., 2015). One of the most commonly used methods for allowing athletes to RTS has been the LSI of the involved quadriceps and hamstrings versus the uninvolved limb to be used as a reference marker through the timing of rehabilitation and at the point of RTS (Abourezk et al., 2017; Logerstedt et al., 2013; Schmitt, Paterno & Hewett., 2012). However, in recent literature it is derived that strength performance deficits do exist and furthermore they exist bilaterally in athletes after ACLR when compared with healthy control groups and the use of preoperative values from the uninvolved limb (Chung et al., 2015; Wellsandt et al., 2017).

Whilst many studies have addressed the use of quadriceps PT LSI (> 90%) as one of the main criteria for 'passing' a RTS assessment (Grindem et al., 2016) it should be be further scrutinised from the work that this study has undertaken. This study found that of the 25 athletes who met inclusion criteria (figure 4), staggeringly, only 28% (7/25) of athletes were sufficiently ready to RTS (table 7). The inclusion criteria used for this study incorporated all athletes who had met ≥ 90% quadriceps PT LSI across repetitions 2, 3 or 4. This criterion differed slightly from the normal ≥ 90% quadriceps PT LSI which would normally be taken from repetitions 1-5 (Pelegrinelli et al., 2018). However, the reason behind taking the value from repetitions 2, 3 and 4 was that we would discard repetitions 1 and 5 due to inertial effects that could take place within these repetition ranges (Undheiem et al., 2015). Additionally, this method allowed us to highlight athletes who can sustain torque production over a repetitive period compared to just the first repetition for instance and producing PT. Many studies use the same approach of disregarding the first and last repetitions to eliminate inertial effects and fatigue during the testing protocol (Baumgart et al., 2018; Crotty et al., 2022; Eitzen et al., 2010; Huang et al., 2017; Pelegrinelli et al., 2018; Welling et al., 2018; Yosmaoglu et al., 2017). Enabling athletes to undertake familiarisation sessions (pre/post season testing) allows them to know the type of testing protocol and the stress the body will be put under; this is pivotal in terms of replicate the same acceleration and deceleration movements required in sport performance. Our study then used an average torque across the six 10˚ torque-angle windows to calculate an LSI reference of the involved/uninvolved*100 expressed as a percentage (Bishop et al., 2018). We found that 78% (18/25) athletes who had been returned to sport because they had met quadriceps PT LSI (> 90%) were actually exposed to an increased risk of re-injury as they displayed residual deficits of <90 % LSI across at least one or more 10˚ torque-angle windows in all three testing protocols (quadriceps CON, hamstring CON and ECC). Furthermore, 16% (4/25) of the participants only had strength deficits at one point across the six 10˚ torque-angle windows across all three tests. Whilst this highlights, they may have only had one apparent section where they missed a >90% cut-off, it proves that residual deficits are current post surgery as this was at the point of RTS (298 ± 108 days). This evidence of residual deficits in LSI for the involved limb falls in line with that of Harput, Tunay and Ithurburn (2021), who saw no change in increase in LSI of the involved limb at six months post-surgery of ACLR. The fact that only 28% (7/25) of athletes managed to record ≥ 90% LSI across all six 10˚ torque-angle windows (20˚- 79˚) across all three testing protocols further illustrates the issue we have when utilising a PT value to solely contribute to the decision-making process at RTS after ACLR. This study has highlighted that the use of a single PT value cannot distinguish residual deficits in muscle strength at the time of RTS; it clearly gives an overestimated and inflated value due to the singular timepoint it is being assessed on, which again lacks reliability (Undheim et al., 2015). The study we have conducted allowed LSI to be conducted using an average across each 10˚ torque-angle window. While this did not take into consideration the PT value at each 10˚ window it did allow for greater reliability on the outcome as the variable was able to be controlled and gave a true representation of torque production across each individual 10˚ window for each testing mode as opposed to one single timepoint which produced the highest torque output before being put into the traditional equation (involved/uninvolved*100). Whilst the PT value was not used as figure across average torque production it was still used to identify an inclusion criterion. The methodology behind using an average torque across each torque window allowed for a truer representation and meaningful value of torque production which could evaluate strength deficits. For instance, rather than using an average of three PT value we felt that an average value across three reps from 30˚- 39˚ (etc per window) would show a far greater understanding of residual strength deficits. Understanding and using a PT value is a common metric but future studies need to evaluate this technique because while it is an easy data point to accrue it does not enhance the strength profiling of an athlete. Knowing that PT can be a misleading value in the sense other data is not analysed is a concern for every clinician, patient, and surgeon. Ultimately, this single value can return athletes back and cost them their careers and have huge ramifications for clubs financially both in medical bills but also player contracts. Eliakim et al (2020) suggest that an English Premier League club often loses an average of £45 million due to injury related decrement in performance per year. Generally, with ACL injury and rehabilitation taking around 9-12 months there can be a lot of money attributed to this costing over the injury period.

Furthermore, in our study of the 72% (18/25) athletes who did not achieve ≥ 90% mean torque LSI across all six 10˚ segments, 78% (14/18) elicited two or more segments that achieved ≤90% mean torque LSI across all six 10˚ segments at quadriceps CON, hamstring CON and ECC contractions respectively, which identifies that more appropriate analysis of torque-angle windows needs to addressed in future research which is similar to conclusions from other research (Harput, Tunay & Ithurburn., 2021; Hart et al., 2022). This reiterates the need for greater conclusive and strategic isokinetic testing procedures so that the reduction of secondary ACL injury is decreased. Thus, the financial implications to athletes and clubs is minimised.

5.5.1 Quadriceps CON LSI

When broken down by isokinetic testing protocols we highlighted that during the quadriceps CON testing only 56 % (14/25) of athletes achieved a ≥ 90% LSI mean torque across all six 10˚ torque angle segments between 20˚-79˚. Of the 44% (11/25) that did meet ≥ 90% LSI across all torque-angle segments, 63% (7/11) of these athletes who had two or more 10˚ segment windows achieve ≤ 90% LSI in knee extension. Subsequently, of the 7 athletes who achieved ≤ 90% LSI at quadriceps torque-angle windows, 85% (6/7) of athletes had at least one segment that achieved ≤80% LSI which is highlighted in red (table 7). It is pertinent to now understand that these residual deficits that are occurring within the torque-angle window are being highlighted mainly between 20˚- 49˚ and 70˚-79˚ knee extension; this is concurrent with similar research that established strength deficits at these RoM (Cinar-Medeni, Hartput & Baltaci., 2019; Read et al., 2022). It is commonly reported that the more symmetrical the quadriceps strength is the greater reduction in knee re-injury rate (Grindem et al., 2016). Furthermore, it is postulated that the modest means of LSI in quadriceps PT has been well documented in their cohort of patients at different timepoints throughout rehabilitation (Barford et al., 2019; Ebert et al., 2018). However, Ebert et al (2021), suggest that between 60˚- 75˚ of deeper knee flexion angles shows significant differences occurring with mean LSIs of 73% and 63%, thus suggesting that significant side to side isokinetic knee strength deficits are missed if the use of PT is the only objective marker measured. Moreover, our findings highlight the intricacies of using an average torque value compared to a PT value to provide a full picture across the RoM. Like our study, Hartput et al (2021), found the involved quadricep and hamstring muscles exhibited consistent increases in muscular strength over the first six months of rehabilitation after ACLR. However only 16% of their 38 male cohort who underwent ACLR achieved a pass rate of > 90% LSI for quadricep and hamstring muscle strength at six months post ACLR. We know that due to quadriceps decrease in muscle strength it is thought to be due to muscle atrophy and AMI which is inevitable after ACLR (Keays et al., 2001; Logerstedt et al., 2013; Palmieri-Smith, Thomas & Wojtys., 2008; Schmitt, Paterno & Hewett., 2012). This indicates why we may well be seeing residual LSI deficits at the deeper knee flexion angles of 70˚- 79˚ and 20˚- 49˚.

It should be considered that when the athletes were split via graft type (table 8 and 9) BPTB (n=13) and HS graft (n=12), of the athletes who had BPTB grafts (n=13) it should be noted that 100% of the athletes had achieved ≥ 90% LSI through knee extension in the mid-range (40˚- 69˚) windows where torque production is at its strongest including the 60˚- 69˚ window where PT occurred. However, those who had a BPTB graft only 46% (6/13) of athletes managed to pass ≥ 90% across all 10˚ torque-angle windows in all three modes of testing. The athletes who had BTB graft, 54% (7/13), and did not pass ≥ 90% across all 10˚ torque-angle windows that 57% (4/7) of athletes had residual deficits in the quadriceps CON testing at the time of RTS in either one or two 10˚ torque-angle windows which came at the outer ranges of movement at knee extension between 20˚- 39˚ and 70˚- 79˚. We know that due to the force- length relationship, specific deficits can remain undetected in quadricep muscle strength at flexion angles <45˚ or <40˚ (0˚ = full extension) Eitzen et al., (2010); Huang et al., (2017). It is important to understand that knee extensor torque generally is at its greatest around the mid-point of muscle contraction, hence the copious amounts of research that deems the angle of PT on quadriceps concentric movements to be around 60˚- 65˚ (Ikeda, Kurosawa & Kim., 2002; Shirakura, Kato & Udagawa., 1992; Slocker de Arce et al., 2001; Tsepis et al., 2004). Consequently, the torque production from knee extensors when in a seated position display the lowest relative value as the angle approaches full knee extension (Hahnn et al.,2011; Kellis, 1998). This further elicits the need for further investigation into the use of torque-angle analysis prior to

RTS after ACLR as we know that deficits greater than 20% are associated with reduced knee function and movement compensations during high loading activities (Palmieri-Smith & Lepley., 2015).

5.5.2 Hamstring CON and ECC LSI

Our findings continued to highlight the need for greater torque-angle analysis at the point of RTS after ACLR as we also demonstrated that there were significantly more reduced LSI between limbs within the hamstrings at late-stage isokinetic testing for both CON and ECC contraction modes. As expressed in table 7 only 52% (13/25) of athletes attained ≥ 90% LSI for hamstring CON and 56% (14/25) for hamstring ECC contractions respectively further showing that the use of a single PT value to identify LSI potentially overestimates the limb symmetry after ACLR at the point of RTS. We know that a breadth of literature associates hamstring strength deficits with a heightened increase in subsequent ACL injury due to the coactivation of the hamstrings in the role of harnessing and supporting the native ACL (Cohen et al., 2014; Delextrat et al., 2020; Ruas et al., 2019). Previous studies have found that persistent hamstring strength deficits in knee flexion angles can persist for many years with deficits often up to 20% at the point of RTS (Ardern et al., 2010; Nomura, Kuramochi & Kukubayashi., 2015; Tengmen et al., 2014; Timmins et al., 2016). This coincides with our research findings which clearly highlight that there is a need for constant analysis for knee flexor strength at the point of RTS after ACLR and throughout the rehabilitation process. Knowing the hamstrings have residual strength deficits throughout both CON and ECC muscle contractions regardless of graft selection suggests that hamstrings need to be optimally loaded to reduce the significant deficits limb to limb. The application of this to the rehabilitation process is vital. Increasing the loading of knee flexor exercises throughout the rehabilitation process can address deficits at the point of RTS. Moreover, it allows clinicians to select appropriate exercises that will target the hamstrings in both a knee and hip dominant exercise to allow greater neuromuscular development which in turn increases muscle mass and the RFD (Read et al., 2021). Understanding that deficits in hamstrings are present even after a BPTB graft shows the importance of incorporating the correct exercises to enhance muscle strength before ging into further explosive work such as CoD, running and sprinting. This is where more than one timepoint of isokinetic testing is required throughout the rehabilitation process because it helps to inform clinical guidance and a return to training and later a RTS. It can also adequately visualise strength deficits over time and gives visual representation to the athlete so that they can understand where they are in the rehabilitation and RTS continuum regardless of time from surgery.

Our study found that in the 12 athletes who did not achieve ≥90% LSI mean torque across the 10˚ angle torque segments for hamstring CON 75% (8/12) produced at least two 10˚ segments where they did not pass ≥ 90% LSI. The results also highlight that 42% (5/12) participants also had at least one 10˚ torque-angle segment that achieved

≤80% LSI across hamstring CON testing. Of the 12 participants who did not achieve ≥ 90% LSI mean torque at all segments, 42% (5/12) had deficits across the full RoM with 60% (3/5) and 40% (2/5) having five or even all six, respectively, 10˚ torque-angle windows at a threshold of ≤ 90% LSI mean torque at hamstring CON contractions. This further suggests that athletes who have undergone ACLR exhibit huge discrepancies across knee flexion angles. The majority of knee flexion deficits occurred < 49˚ which concurs with previous research where we know that shallow angles of knee flexion occur with the MOI for ACL injury (Della Villa et al., 2020; Grassi et al., 2020). Moreover, research ascertains that a 10.6-fold greater risk of re-injury after ACLR for every 10% decrease in knee flexor to extensor strength ratio for the involved limb within a professional soccer cohort (Kyritsis et al., 2016). We should note that findings in this study found the angle of PT to occur at 30˚ for the involved side and 28˚ for the uninvolved side, however, looking at our analysis of the 18 athletes who did meet ≥ 90% LSI across all six windows across all three conditions (table 7), 50 % (9/18) and 44% (8/18) achieved ≤ 90% LSI in torque angle windows 20˚- 29˚and 30˚- 39˚ respectively. These results also yielded that 80% (4/5) of those who had deficits in the 70˚- 79˚ on hamstring CON testing presented with < 80% LSI. These results could be based on the fact we know hamstrings muscle activation after ACLR can take up to 6-8 weeks for the donor site to be able to put under adequate functional stress due to the taking of the graft and morbidity of the hamstring tendon (Buerba et al., 2021). The results in the hamstring CON testing align with previous research which consolidates that angle-specific torque profiles were, in general, lower for hamstrings than quadriceps across the majority of the six 10˚ windows (Baumgart et al., 2018; Cinar-Medeni et al., 2019; Huang et al., 2017; Tengman, Schelin and Hager., 2022).

Hamstring ECC testing yielded significant concern in our cohort as only 56% (14/25) achieved ≥ 90% LSI when calculated with the average torque values. Meaning that 44% (11/25) did not meet a 90% LSI cut-off. Of these 11 participants 64% (7/11) had at least two 10˚ torque-angle segments that highlighted less than 90% LSI. It is evident (table 7 and 8) that hamstring ECC torque production yielded the most significant deficits for LSI of the involved and uninvolved limb. It was apparent that 55% (6/11) of athletes had at least four segments where they achieved < 90% LSI with 16% (1/6) recording ≤ 80% LSI across all six segment windows. For clarity we can highlight that the most affected windows were between 50˚- 79˚ with the majority of <80% LSI coming in the 60˚- 69˚ window where 71% (5/7) of athletes did not attain the required 'pass' rate and likewise at 70˚- 79˚ window where 56% (5/9) athletes could only achieve ≤80% LSI. We know that this could have enormous detrimental effects on athletes, as the ECC contraction of the hamstrings occurs in most field base sports and high velocity movements when sprinting, decelerating, and cutting manoeuvres. All of which are precursors to MOI of ACL injury (Della

Villa et al., 2020). We know that as the knee comes into less degrees of knee flexion (<40˚) this is at the point the ACL is taking most strain and therefore we need the hamstrings to be strong in a lengthened position in order to help reduce the stress placed on the ACL (Delextrat et al., 2020). We can also postulate that the majority of athletes who did elicit residual deficits in the hamstring CON and ECC LSI actually underwent ACLR with a HS graft. Our results (table 9) highlight that of the 25 athletes those who underwent HS graft (n=12) only 8% (1/12) actually achieved ≥ 90% across all torque-angle analysis in all contractions. We can summarise that 75% (9/12) of those with HS graft presented with residual deficits in at least one 10˚ segment across all torque-angle analysis for LSI in both hamstring CON and ECC testing at the point of RTS. Consequently, we can agree with the hypothesis that it is clear to see there are residual deficits across knee flexion angles in hamstring muscle strength. This study has provided evidence to suggest that functional rehabilitation needs to be targeting specific knee flexion exercises that strengthen the hamstrings throughout the full RoM from the early stages of rehabilitation. Hamstring injuries are one of the most commonly reported injuries in team sports (Dick et al., 2007; Van Dyk, Behan & Whitley., 2019). So, the focus needs to be around understanding the mechanics of the hamstrings and how this biomechanically affects sporting performance. We understand the anatomical background of how ACL injuries occur when there is a shift in the muscular and neuromuscular activation paradigm, but we now need to enhance the awareness and importance of specific torque-angle strengthening. This should be addressed as research moves forward so that it can start to influence rehabilitation in the early stages of post-operative care through to the RTS. Any excessive imbalance of the agonist and antagonist can produce an increased risk of hamstring strains and thus increasing stress on the ACL. Utilising evidence from Bourne et al., (2015) and Fousekis et al., (2011) indicate that in rugby and soccer players, an upward trend of 15% interlimb symmetries within the hamstrings can result in an increased risk of hamstring strains. Ultimately, we need to then consider this information when planning the rehabilitation from ACLR because if we do not look to appreciate the mechanics of the hamstring, specifically, in the long lever positions of ECC contractions which represent potential risk of injury to the hamstring and therefore neurological stress on the ACL and its mechanoreceptors. Meaning that athletes will ultimately be predisposed to an increased chance of ACL injury and re-rupture (Grindem et al., 2016; Kyritsis et al., 2016). Understanding these processes allows clinicians to adapt and underpin rehabilitation appropriately according to the graft type and residual deficits that have been identified in this study. By incorporating ECC training modalities into the rehabilitation programme it should help to mitigate residual strength deficits in knee flexors across torque-angle windows at the point of RTS, while also adding a protective element against hamstring strains as this type of training can shift the angle of ECC hamstring PT towards the longer muscle lengths (Cohen et al., 2015; Delextrat et al., 2020).

5.5.3 H:Q Ratio

Our results highlighted that a H:Q conventional ratios were 0.6 for the involved side and 0.61 for the uninvolved side. This ratio is hamstring CON/quadriceps CON torque to give a value that can be attributed to a ratio deeming the relationship of muscular strength between the muscle groups. The FR in our study provided 0.84 for the involved side and 0.80 for the uninvolved side (hamstring ECC/quadriceps CON). This gives us an insight at the point of RTS whereby we can quantify if athletes are significantly weaker in the hamstrings to the quadriceps. It allows clinicians to be able to characterise muscular strength deficits which could potentially cause an increase in ACL injury risk if not mediated (Eustace, Page & Greig., 2019). In their study they found that the data produced larger deficits for the FR (H:Q) of the involved limb in comparison to the uninvolved limb and control group. Additionally, it was suggested that the reason for the larger deficit was due to the impaired knee extensor muscles at the point of RTS (Eustace, Page & Greig., 2019). Highlighting these strength deficits allows us to determine a strength profile for individual athletes after ACLR. It allows clinicians to fully understand the extent to which athletes are not appropriately back to athletic function, yet some athletes who may be back training because they functionally can-do tasks in a controlled environment may not be appropriately conditioned at the optimal muscle strength capacity to RTS. This further elicits evidence that conventional ratios offer a diminished view of the full-strength window throughout a full RoM, thus needing to optimise alternative H:Q ratios (Ruas et al., 2019). Considering and highlighting the bilateral strength deficits at the quadriceps and hamstrings after ACLR is clearly now becoming more apparent to be able to focus rehabilitation specifically to windows in which they are lacking muscular strength. The issue with FR H:Q is that it does not take into account that both PT values for knee extensors and flexors occur at differing angles (Eustace, Page & Greig,., 2017; Ruas et al., 2019). Further highlighting the importance of building a strength profile of an athlete for RTS, in particular needing to have a number of ways to analyse the data that is recorded as one piece of data is not enough to confirm a RTS status for isokinetic muscle strength post-ACLR. Huang et al., (2017) demonstrated that the H:Q conventional ratio has shown to offer greater difference of peak moment of injured and non-injured knee and has become clear that has less favourable outcomes during rehabilitation. They suggested that an elevated H:Q ratio resulting from a diminished quadricep strength may indicate a strength imbalance, again, reiterating the need for further in-depth torque-angle analysis.

Generally, we know that pivoting athletes and soccer players illicit greater torque outputs and sustain the torque output over a greater RoM and time in ACLR athletes (Pelegrinelli et al., 2018). However, we also know that AMI inhibits neuromuscular activation and intensity levels bilaterally and unilaterally after ACLR (Buckthorpe et., 2019). This can hinder the H:Q ratio as we know the RFD can be affected by deficits of 30% after muscle strength is restored post ACLR (Angelozzi et al., 2012). The reason for understanding the clinical importance of H:Q ratios are to be able to try and mitigate inflated estimations when muscular strength testing at the point of RTS and throughout the rehabilitation process. Testing throughout the rehabilitation process allows clinicians to determine if muscular strength and RFD is increasing with time post ACLR, it also offers a baseline of data to work from in terms of identifying muscular imbalances, providing an athlete with the utmost care. A shift in the angle of PT in the hamstring muscle can reportedly increase the susceptibility to injury and makes the hamstrings more prone to damage from ECC loads (Yosmaoglu et al., 2017). However, Cohen et al., (2014) concluded that a loss of ECC hamstring torque and H:Q ratio would increase the risk of hamstring injury. Which highlights the need for screening ECC hamstring strength regularly but also increasing dosage of ECC hamstring exercises to mitigate injury which could lead to ACL rupture. Delextrat et al., (2020), found that though extensive strengthening exercise interventions, ECC strength could be increased and thus moving the angle of PT to a longer lever length which offers a protective element to the ACL and decreases the risk of injury.

Huang et al., (2017) suggested that ACL ruptured limbs presented greater angle-specific torque H:Q in both conventional and functional ratios which followed similar findings by Hiemstra et al., (2007) who both found patients produced greater angle-specific torque at around 30˚- 40˚ knee flexion. Again, leaning towards a quadriceps strength and activation deficit in ACL injuries, thus increasing the deficit at more extended knee angles and increasing the H:Q ratio (Ruas et al., 2019). This furthers the point that monitoring muscular strength imbalances through torque-angle windows needs to be recommended after ACLR, not only will it offer a safer RTS, but it will optimise post-operative rehabilitation from early to late stages. Nonetheless, like any scientific research, angle-specific torque H:Q should be interpreted with caution as it may vary due to graft types and gender, but also less reliable than traditional H:Q ratio (Ayala et al., 2012). However, angle-specific torque H:Q ratios may be in part more useful than given credit for. We know that ECC muscle contractions can fatigue muscles on isokinetic testing protocols but if athletes are given familiarisation sessions this may actually give a greater representation of functional H:Q ratios, it would also aim at reducing the torque variability at extreme angles (Ruas et al., 2019). Evangelidis, Pain and Holland., (2015) found that angle-specific torque led to erroneous conclusions when they measured at 5˚ intervals. Our H:Q ratios ranged from 1.40 to 0.46 in the involved side and

1.50 to 0.45 in the uninvolved side for conventional ratios and from 1.94 to 0.60 in the involved side and 1.96 to 0.59 at larger knee flexion angles on the uninvolved side. The results of the study when comparing the involved to the uninvolved side for conventional ratios had no more than a 0.05 difference in ratio at any of the six 10˚ angles except 20˚-29˚ when it was 0.1 difference in ratio (table 5). Additionally, the same was to be said for the FR H:Q when comparing the involved to uninvolved side where the biggest difference between either side at a window was 0.04. Although the differing ratio between torque-angle window one and six was 1.34 and 1.37 respectively (table 6) which is like that found by Read et al., (2022). However, most studies use PT to conduct H:Q ratios, both torque-angle specific and normal, and this already skews the ratios due to the PT value being obtained at different angles thus not reflecting dynamic knee stabilisation. Whereas our study used the average torque calculated at these windows to then conduct the H:Q conventional to functional ratios. This at least in part offers a more reliable and reputable figure of torque produced and H:Q ratio, as it has looked at torque across the whole 10˚ window and not just a singular time point, proving that targeted torque-angle windows can produce clear findings than a PT value.

Consequently, torque-angle H:Q ratios both conventional and functional should form part of a routine checklist along with LSI that uses average torque production across torque-angle windows when conducting any isokinetic strength testing. It can provide specific information throughout a full RoM of the knee compared to just a conventional and functional PT H:Q ratio and PT LSI. While this would be an ideal, there is no harm in understanding and collecting PT and the angles of PT to utilise as an objective marker against normative data but our research highlights why a PT value in any sense may only just scratch the surface, when advocating a safe RTS after ACLR with isokinetic strength testing. Finally, the use of torque-angle ratios is relatively new, therefore, many researchers do not tend to use this because of the lack of evidence to back up this criterion (Ruas et al., 2019). To continue moving forward in research more of this work needs to be attained to highlight and form a normative database for torque-angle windows. This would help to mitigate future ACL injury and to help the formulation of rehabilitation process that incorporates extensive CON and ECC work for both the hamstrings and quadricpes after ACLR up to the point of RTS.

5.6 Conclusion

Current research on late-stage rehabilitation and at the time of RTS identified there was potential to propose of further stringent criteria and reflective factors that may be linked to future re-injury risk and performance (Buckthorpe., 2019; Buckthorpe & Della Villa., 2020). While our study would support this hypothesis, in relation to more stringent criteria on isokinetic testing, it should also be brought to attention that when passing criteria for RTS and adding in more testing criterion the likelihood of athletes managing to 'pass' all these significantly reduces (Kyritis et al., 2016). Loscaile et al (2019), identified that only 26% of patients meet current criteria at six months after ACLR which concurs with research from Welling et al (2018), who found that only 11% of patients met RTS criteria after nine months. Therefore, making the criteria even harder will likely not solve the problem. Conversely our findings highlight that while testing criteria is objective and those going through RTS may not meet isokinetic ≥ 90% LSI across all torque-angle analysis at the time of RTS, it would be prudent to enhance the stringent nature of isokinetic testing both at the time of RTS and throughout the rehabilitation process otherwise as clinicians we are ultimately giving a disservice to our athletes and putting them back on the field with an increased chance of subsequent injury or re-rupture.

While a growing body of literature has highlighted that a RTS after ACLR should be deemed as a nine month minimum requirement to reduce the risk of re-injury (Grindem et al.,2016), our study has highlighted that even with a nine month period of rehabilitation before the point of RTS, only 28% (7/25) were able to pass ≥ 90% LSI of quadriceps and hamstrings muscle strength for CON and ECC (hamstrings only) testing across a 60˚ torque-angle window. Additionally, a study by Kotsifaki et al., (2023) has suggested that time is no longer a main criterion for RTS but other modalities and such as strength and physical capacities should be met with a viewpoint of time being a secondary factor. Pertinently, contributing to the ever-growing literature suggesting that torque-angle analysis across a full RoM should be a necessity at the point of RTS for athletes and used throughout rehabilitation to target specific areas of muscular strength deficits in knee extension and flexion (Buckthorpe & Della Villa., 2021; Hart et al., 2022Read et al., 2021). Rather than the use of a single PT value that can be derived from a singular timepoint and consequently offer an over inflated value that has so often been used as the 'golden bullet' in which clinicians allow athletes to RTS.

5.7 Limitations

As with any research, there are methodological and practical limitations within this thesis. It is important to recognise and acknowledge these and the difficulties they present when looking to generalise findings to a population. The key limitations have been outlined below:

5.7.1 Accuracy of using LSI as an equation for RTS

Although the thesis has taken several years to complete there has been research conducted around different use of LSI % for RTS as discussed explicitly in the literature review. The ambiguity of the use of LSI as a reference marker for RTS has been highlighted in previous research by Bishop et al., (2018). It has been widely reported that while LSI can offer an objective marker by which a decision can be made, clinicians are assuming that the contralateral limb is deemed an appropriate marker to use as a comparison to determine knee function using the LSI equation (Benjaminse, Holden & Myer, 2018; Wellsandt, Failla & Synder-Mackler, 2017). This could result in misleading data that could potentially put athletes at risk of RTS. However, this is why the thesis used an average torque value at each 10˚ torque-angle window in order to enhance the validity and reliability of the data across the strength profile (Ebert et al., 2021; El-Asker et al., 2017). It would be deemed critical for clinicians to have baseline data of their athletes for muscular strength across the knee extensor and flexor RoM. This would concentrate on a similar study that used pre-operative values as a baseline for muscular strength capacity. EPIC values which were used to identify deficits in muscular strength following ACLR (Wellsandt, Failla & Synder-Mackler, 2017). Having baseline data as a reference point allows clinicians to accurately rehabilitate athletes after ACLR to 'pass safely' RTS criterion, without having to use the contralateral limb as a reference point when research suggests the deconditioning of the uninvolved limb (Ward et al., 2015). The use of baseline data would then be able to conform to build a database of normative data globally, in turn, leading to successful RTS from any injury but specifically ACL injury (Hart et al, 2022; Tengman, Schelin & Hager, 2022). The influence of having baseline data to compare athletes, post-operatively, is like 'gold dust'. Whilst having normative values gives an idealistic start point, we know individuals do not sit on the same trend line when it comes to strength capacities. Therefore, the benefit of having pre-operative data has a huge influence on how specific and detailed the rehabilitation plan can be from the outset.

5.7.2 The use of average torque during LSI % equation

Whilst use of PT has been explicitly stated as questionable, it is a metric that can be used, but if doing so should not be used as a lone value to dictate if RTS criterion has been met. PT can be utilised alongside other metrics as we have discussed throughout the thesis to convey a holistic and rounded approach to strength profiling. The interpretation of average torque values should be interpreted with care. Whilst they offer valuable objective data; they will also potentially lower the LSI % due to using an average value which would smooth the value as opposed to a peak value. Although this could potentially lower the LSI % within knee extensor and flexor strength it would give greater reliability as the value would consistently give a greater representation at each specified torque-angle window than a PT value which has had reliability questioned previously due to its singular timepoint (Undheim et al., 2015). Over a period of time this would ultimately create enough data to give an indication of muscular strength. Evidence suggests that a PT value is useful to gain an insight into an athletes peak score but we also want to know if that torque-production can then still be produced and sustained over a short bout of explosive contractions that correlate directly to sporting actions which will be demanded when an athlete RTS.

5.7.3 Torque-Angle RoM Analysis

For the analysis in the thesis, we only looked at analysing data within a 60˚ window from 20˚- 80˚ knee extension and flexion. We chose not to investigate differences in torque at knee angles <20˚ or >80˚; this is due to the torque measurements at these extremities of the knee extension and flexion RoM being likely to require isometric assessment for more complete profiling at the outer ranges (Ruas et al., 2019). It is to be understood that inertial effects can cause misrepresentative figures in these extremes and therefore our analysis chose to focus solely on 60˚ where previous research has highlighted angles close to the MOI for ACL injury (Ebert et al., 2021; El-Asker et al., 2017; Hart et al., 2022; Read et al., 2022). To date this thesis is only one of two pieces of research which identifies findings from 60˚ RoM for knee extensors and flexors, along with a study from Hart et al (2022), who analysed a 70˚ window on both knee extensors and flexors. Whilst the analysis used a 60˚/s angular velocity to conduct the IKD strength testing it should be thought that similar studies in the future could be conducted at greater angular velocities such as 120˚/s, 180˚/s, 240˚/s, 300˚/s to provide greater replication of sporting actions that require rapid contractions (Eustace, Page & Greig., 2017). However, this would not necessarily provide further in-depth analysis of torque production across torque-angle windows. While greater speeds may mimic sport specific actions such as kicking a football or accelerating and decelerating where rapid contractions of knee extension and flexion occur, it will also further reduce the isovelocity on the angular range because of the time taken to accelerate the limb from static to the required angular velocity at the start of each knee extension and flexion contraction (Baumgart et al., 2018). Thus, reducing the reliability of faster angular velocity data meaning clinical interpretation should be taken with caution when addressing higher angular velocities and attributing to sport specific requirements post ACLR such as evaluating strength deficits comprehensively (Read et al., 2021).

A final torque-angle analysis may also wish to consider looking at quadriceps ECC muscle strength too, this was not able to be done in this cohort as data was not recorded for this mode of contraction. However, this piece of information may well help to give an even greater picture on residual strength deficits in knee extensors at the point of RTS after ACLR.

5.7.4 Study Design and Analysis

This thesis used retrospective data that was collected and therefore had only one timepoint of data for assessment criteria at the time of RTS. It would be prudent to have been able to have athletes' data at consecutive timeframes e.g., 3, 6, and 9 months before RTS after ACLR. This would add rigor to the current study and help to identify where residual strength deficits were occurring throughout the rehabilitation process. This could enable clinicians to modify and adapt strategies to fulfil muscular strength deficits at knee extensor and flexors, and to exhibit ≥ 90% LSI across all average torque analysis across the full torque-angle windows demonstrated to enable a 'safe' RTS compared with current literature of quadriceps PT LSI % for RTS protocol. Moreover, it may be useful to implement a rolling average as a data analysis technique to explore if this has a greater influence on eliciting muscular strength deficits in torque-angle windows. It may be useful to incorporate Isomapping to be able to show the whole torque curve angle to help identify and present future research findings.

5.7.5 Participant Sample

This retrospective study comprised of twenty-five male professional athletes from the Middle Eastern and Gulf regions. Although power calculations were completed a priori, sample sizes were ultimately influenced by athletes who had sustained ACL ruptures and required ACLR. This is a catastrophic injury and therefore we can only use the athletes who have met this criterion at this point in time. Due to the heterogeneous sample, it reduces the ability of generalisation as we have looked at a specific population where findings could in part be environmentally bias or cultural processes that have influenced outcomes. Although, generalisation is then hard to apply globally, this sample has added a unique dataset to the sparse literature in Middle Eastern and Gulf athletes (Rekik et al., 2018). When interpreting the findings from the study, it should be considered we did not include a healthy control group. Research has indicated that isokinetic strength on the contralateral limb is reduced compared to healthy controls following ACL reconstruction. (Chung et al., 2015). Therefore, it would be recommended that a control group could potentially be implemented for future research as a comparison for the ACLR athletes. Also due to the nature and seriousness of an ACL injury, the cohort used at the time was dependent on those who had this catastrophic injury. It would be prudent to have a greater sample size which may yield similar results and/or produce more statistically significant findings due to the increase in the cohort. Moreover, the participant sample could only be attributed to male athletes who have undergone ACLR in this study. Therefore, findings from this study could not be inferred for female athletes, as previous research has indicated gender differences and incidence rates in ACL injury occur differently in females (Ireland., 2002; Quatnam & Hewett., 2009). Future research should look to continually build on this population in both professional male and female athletes. It would be prudent to identify characteristics of this population to see if there are any physiological differences comparatively with other researched populations. This would potentially help with identifying if anatomical differences are present in this population.

5.7.6 Graft Type

A limitation of this study is that both surgeons who performed the ACLR were from a single centre and predominantly performed BTPB and HS tendon grafts. While we did not look to analyse graft types in relation to causing potential risk of re-injury, research should look to explore graft types as a potential factor that can affect RTS and rehabilitation (Buerba et al., 2021). Literature suggests that clinical decision-making is not standardised between clinicians and surgeons but more in-fact that the graft type is typically influenced by a surgeon's preference and training (Duchman, Lynch & Spindler., 2017; McDermott., 2013). Future research should look at the decision-making principles of graft types based on a united athlete centred approach. This will then help to dictate what graft type is used for surgery and the implications to RTS and accelerating rehabilitation. Finally, graft type has a huge influence on how the athlete's rehabilitation programme is applied. This means that graft selection has to be considered when determining the athletes ACLR. The published literature describes graft selection as a key indicator for RTS criteria, as we have found in this study, whilst HS graft is now common practice it also carries clear strength deficiencies at late-stage rehabilitation and RTS. Therefore, an interesting follow-up study should identify athletes to see if deficits are still present but also look to expand and identify graft selection techniques based on strength deficits post ACLR.

5.8 Practical Applications

The overarching aim of this thesis was to enhance the quality of isokinetic testing performed at the point of RTS within professional Qatari athletes who had undergone ACLR. The thesis aimed to identify if current RTS isokinetic testing showed residual strength deficits when compared to a strength profiling of knee extensor and flexor across a full torque-angle RoM.

Torque-angle specific analysis has been conducted in previous literature but is something on the whole that has been dismissed in ease of a PT value and subsequent LSI % of knee strength. It is plausible to think that the integration of torque-angle specific windows, can highlight and offer a quantifiable marker in which residual strength deficits occur post ACLR. This research will allow clinicians to start to question the approaches taken at the time of RTS when using isokinetic testing procedures. This recommendation is, timely, based on findings from similar studies by Hart et al., (2022); Read et al., (2022) and Tengman, Schelin and Hager., (2022), who have all recommended that angle-specific analysis identifies residual strength deficits that are not exhibited in traditional PT analysis alone in knee extensor strength. Due to the neuromuscular deficits found in knee extensor strength after BPTB graft and deficits in knee flexor strength after HS graft at larger knee flexion angles, ACLR rehabilitation should include assessment of isokinetic testing across specific torque-angle windows to help address muscular strength deficits during ACLR rehabilitation (Hart et al., 2022; Read et al., 2022; Read, McAuliffe & Thomson., 2021; Ruas et al., 2019). This would then enable athletes to be RTS with full function of knee extensor and flexor muscle strength and elicit a greater reduction in the chance of secondary ACL injury.

Chapter 6 Future Research

This thesis has statistically suggested that there while there is no definitive appreciation of graft type and toque-angle analysis relationship, there was enough evidence through medium effect sizes (Cohens, 1998), to infer there is interaction between both graft type and 10˚ torque-angle windows across the analysis. As expected, the six 10˚ torque angle windows did offer a significant difference which was to be expected as average torque generally increased as the 10˚ window increased. However, the thesis has generated novel findings around LSI % at torque-angle windows, but as a result has raised more questions for future direction. There is a considerable amount of work to do within the field of torque-angle analysis during isokinetic testing for RTS after ACLR in adolescent soccer and pivoting sports before we can make any conclusive recommendations for athletes and practitioners. The undertaking of this thesis has identified some clear areas in need of further research, of which the most prominent are outlined below to stimulate the progression of the field.

Assessment criterion for RTS should ideally look to incorporate and address angle-torque windows for analysis when deciding if an athlete is 'safe' to RTS to reduce residual strength deficits in key muscle groups after ACLR. Future research should look to identify strength profiling of athletes to co-ordinate and formulate rehabilitation plans in ACLR cohorts that can precisely target specific angle windows whereby athletes are struggling to restore full neuromuscular function. It is imperative that further research looks to address muscular strength deficits early in the rehabilitation process to optimize knee function and reduce the chance of re-injury (Ithurburn et al.,2018; Kuenze et al., 2015; Schmitt, Paterno & Hewett, 2012).

Future research should look to further assess the strength capacity of both the involved and uninvolved limb to determine the accuracy of LSI % and appropriate utilization of this throughout the recovery process (Harput, Tunay & Ithurburn, 2021). This thesis highlights the issues that arise using PT as the sole indicating value for calculating a LSI for athletes at RTS timing. We effectively need to look at using an average torque value across torque-angle windows to re-affirm limb symmetry at the point of RTS to closely identify if the athlete passes a > 90% LSI across a full RoM. Any deficits that are then still deemed to be below this cut-off can be used to prescribe more precise rehabilitation in these joint angle windows of knee flexion before re-assessing and RTS if criterion is met.

Specific research to this study would look to have a follow-up with the cohort of athletes whose data were used retrospectively. Within this follow-up study it should look to ascertain if those who had residual deficits after being deemed 'safe' and 'passed' RTS criteria (> 90% PT LSI of quadriceps) still are quantified as having residual deficits and/or if those deficits have decreased or in fact increased. It would also be prudent that we understand any future injuries they have sustained from potential hamstring and quadricep strains, or more severely, knee injuries such as potential re-rupture of the ACL, contralateral ACL injury or any other catastrophic knee injuries. Alongside this it would be beneficial to identify how many of the athletes are still playing at the professional level they were previously playing at prior to ACLR and if any of this athletic cohort are either playing at a lower level or sport or no longer playing sport at all.

Finally, research should look to conduct a rigorous strength profiling on athletes who undergo ACLR at time points throughout the rehabilitation process (3, 6 and 9 months) and before RTS, this would establish a clear picture of muscular strength throughout the process as well as throughout a RoM. This study has highlighted the need to further elicit isokinetic strength deficits using specific torque-angle window analysis. Crucially it also creates questions around how we form normative data values and if they should change based on not just using a PT value, but also what we class as baseline data to return athletes back to an equivalent strength and playing status post ACLR. We recommend that future research should scrutinise torque-angle windows to identify and rigorously improve isokinetic testing procedures to help restore and maintain knee extension and flexion strength throughout the rehabilitation process so athletes 'pass' RTS testing after ACLR rather than just using traditional PT values. Torque-angle H:Q ratios both conventional and functional should form part of a routine checklist along with LSI that uses average torque production across torque-angle windows, when conducting any isokinetic strength testing as it can provide specific information throughout a full RoM of the knee compared to just a conventional and functional PT H:Q ratio and PT LSI. While this would be an ideal, there is no harm in understanding and collecting PT and the angles of PT; but our research highlights why a PT value may only just scratch the surface, overestimating and giving misleading interpretation when advocating a safe RTS after ACLR with isokinetic strength testing.

Chapter 7 References

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