Strength and power assessment in rehabilitation: profiling the athlete's return to sport journey following ACL reconstruction

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Strength and Power Assessment in Rehabilitation: Profiling the Athlete's Return to Sport Journey Following ACL reconstruction

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SUBMISSION FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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ABSTRACT

Residual deficits in athletic performance are common despite rehabilitation guidelines following anterior cruciate ligament (ACL) reconstruction including criterion-based progressions to protect healing structures, ensure safe restoration of fundamental physical capacities, and guide appropriate return to sports (RTS) activities. The aim of the proposed research was to examine strength and power in the rehabilitation pathway of soccer players following ACL reconstruction. This enabled us to explore interrelationships between physical capacities, movement strategies, and subsequent injury risk. These data were also compared with pre-injury values and matched controls to more fully examine the overall level of physical preparedness following ACL reconstruction, and to examine the validity of alternative approaches to determine RTS status such as composite physical capacity profiling. To address our aims, a systematic review was completed to examine the physical ability of athletic populations in the later stages of rehabilitation in comparison to healthy controls. The results showed deficits in knee peak extension and flexion in adult males at more than 6 months post ACL reconstruction, which were influenced by graft type, and can be mitigated by targeted rehabilitation programs. Insufficient evidence was available to examine rate of force development and reactive strength. The relationships between fundamental physical capacities and biomechanical variables during dynamic movement tasks were then explored through a narrative review using a structured search criteria. Quadriceps strength and rate of torque development explained a moderate portion of the variance in aberrant kinetic and kinematic strategies commonly detected in ACL reconstructed cohorts in the later stages of rehabilitation, prior to RTS. Increasing our understanding of these inter-connected aspects is required to improve rehabilitation outcomes and to reduce the risk of secondary injury following RTS. The findings from our comprehensive review of the available literature led us to explore the recovery pattern of strength and power qualities during rehabilitation and at the time of RTS relative to pre-injury baseline data and those of healthy matched controls. We also examined the effect of these physical qualities has on performance and task execution during tasks which may be associated with subsequent re-injury risk. In addition to the systematic review, three experimental studies were designed each with specific aims.

The aim of study 1 was to examine changes in strength and power characteristics at the time of RTS relative to pre-injury baseline data and healthy matched controls. The main finding was that strength and power in professional soccer players at RTS following ACL reconstruction

were often reduced compared to preinjury values and controls. Compared to pre-injury, ACL normalised quadriceps peak torque of the involved limb, SLCMJ height and Reactive Strength Index modified (RSImod) were reduced following ACL reconstruction, even after the completion of rehabilitation. No significant reductions in bilateral CMJ height, RSImod and relative peak power were indicated at RTS in the ACL group when compared to pre-injury values, but deficits were present relative to controls. The uninvolved limb significantly improved quadriceps and hamstring strength from pre-injury to RTS. No significant differences from baseline were shown in SLCMJ height, power and reactive strength of the uninvolved limb following ACL reconstruction.

In study 2 we investigated if greater physical capacity results in different SLDJ mechanics in adult male soccer players following ACL reconstruction. Moderate to large significant differences between the ACL reconstructed and uninjured limb in SLDJ performance ($d = 0.92 – 1.05$), kinetic ($d = 0.62 – 0.71$) and kinematic variables ($d = 0.56$) were evident. Stronger athletes jumped higher ($p = 0.002$; $d = 0.85$), produced greater concentric ($p = 0.001$; $d = 0.85$) and eccentric power ($p = 0.002$; $d = 0.84$). Similar findings were present for RSI, but the effects were larger ($d = 1.52 – 3.84$). Weaker players, and those who had lower RSI, displayed landing mechanics indicative of a “stiff” knee movement strategy and this may be indicative of heightened injury risk.

The final experiment chapter (study 3) examined the utility of the Total Score of Athleticism (TSA), a composite score including strength, power, and reactive strength assessments to aid RTS decision making, moving beyond the current practice of limb symmetry thresholds and their inherent limitations. A large difference was evident between ACL reconstructed and uninjured players in TSA score ($d = 0.84$). For every additional increase of one unit in the TSA, the odds of belonging to the ACL reconstructed group decreased by 74% (95%CI 0.19, 0.56). A case series also showed there was a higher frequency of low TSA scores in players who sustained a second injury following RTS. These preliminary findings indicate the TSA may be a useful RTS readiness tool and can be used to set benchmarks, and rehabilitation goals for restoration of physical performance.

This thesis provides an original and significant contribution to the existing research. The cumulative findings suggest that: i) strength, power and reactive strength are reduced in elite male professional soccer players at the later stages of rehabilitation and at the time of RTS; ii) these have detrimental effects on kinetic and kinematic variables in dynamic tasks, with weaker players who also have a lower RSI displaying aberrant strategies commonly associated with increased re-injury risk; iii) when assessing recovery of physical capacities, clinicians and coaches should consider both absolute scores on each limb and not just symmetry values. In situations where baseline pre-injury data are not available, comparisons to uninjured matched controls should be made to ensure minimum standards are met; and iv) a TSA can be used to aid RTS decision making due to its ability to differentiate between injured and un-injured athletes, and preliminary evidence suggesting TSA scores are likely to be lower in players who sustain a re-injury after RTS. Further research could prospectively monitor rebounding tasks (e.g., SLDJ) performance and biomechanics, with the implementation of wearable technology (e.g. IMU system) and include these data along with the existing tests which comprised the TSA in the current thesis. Also, a broader range of physical capacities (e.g. aerobic fitness, speed, change of direction, etc.) could be added to our TSA to ensure the all relevant physical performance characteristics are assessed. Using this broader test battery and subsequent TSA composite profile, prospective analysis of secondary injuries following return to sport is warranted to more clearly elucidate its ability to identify associations with re-injury risk.

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Chapter 4: Maestroni, L., Papadopoulos, K., Turner, A., Korakakis, V., & Read, P. (2021). Relationships between physical capacities and biomechanical variables during movement tasks in athletic populations following anterior cruciate ligament reconstruction. Physical Therapy in Sport, 48, 209-218.

Chapter 6: Maestroni, L., Turner, A. N., Papadopoulos, K., Cohen, D., Sideris, V., Graham-Smith, P., & Read, P. (2023). A comparison of strength and power characteristics prior to anterior cruciate ligament rupture and at the end of rehabilitation in professional soccer players. Sports Health.

Chapter 7: Maestroni, L., Turner, A., Papadopoulos, K., Pedley, J., Sideris, V., & Read, P. (2023). Single leg drop jump is affected by physical capacities in male soccer players following ACL reconstruction. Science and Medicine in Football.

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Key terms / Glossary

ACL – anterior cruciate ligament

CMJ - countermovement jump

SLCMJ - single leg countermovement jump

SLDJ – single leg drop jump

RFD – rate of force development

RSI – reactive strength index

RTS – return to sport

TSA – total score of athleticism

CHAPTER 1 – PREFACE

1.0 Introduction

Injuries have a detrimental impact on team and individual athletic performance. The available data suggest an interaction between injury, performance, physical outputs, and success, at both a team and individual level (Hagglund et al. , 2013, Williams et al. , 2016, Windt et al. , 2018). Several studies have reported that a previous injury may increase the risk for subsequent injuries (Arnason et al. , 2004, Esteve et al. , 2018, Fulton et al. , 2014, Hagglund et al. , 2006, Hägglund et al. , 2012, Toohey et al. , 2017). This raises the question of whether persistent deficits have been fully assessed and targeted before athletes return to play (RTP). Put simply, should a greater emphasis be placed on increasing general physical preparedness and promotion of a return to performance strategy as a means of tertiary prevention (Jacobsson and Timpka, 2015)?

Research estimated that 1 in 29 female athletes and 1 in 50 male athletes sustained an anterior cruciate ligament (ACL) injury in a window ranging from 1 season to 25 years (Montalvo et al. , 2019). The season prevalence of anterior cruciate ligament (ACL) rupture in male elite level soccer players is about 1.5% (Niederer et al. , 2018). In several European men's professional first leagues an incidence of 0.066 ACL ruptures per 1000 hours of soccer has been reported (Waldén and Hägglund, 2016, Waldén et al. , 2011). While the incidence is relatively low, there is a high burden of these injuries. In elite athletes, this often results in surgical ACL reconstruction and return to sport (RTS) times on average ~ 12 months (Lai et al. , 2018a, Schiffner et al. , 2018). This is often accompanied by an increased risk of new knee injury (ipsilateral and contralateral), early onset of posttraumatic osteoarthritis, and sports performance deterioration (Culvenor et al. , 2015, Lai, Ardern, 2018a, Lai et al. , 2018b, Larsen et al. , 1999). Not surprisingly, it is one of the most researched sports injuries in the medical literature. ACL injuries typically occur during activities that involve abrupt deceleration or change of direction when the foot is planted (Pua et al. , 2008). Although there is a high rate of return to sport overall (81%-82%), the rate of return to competitive sports is low (44%-55%) (Ardern, 2015, Ardern et al. , 2011b). These data appear to be dictated by fear of re-injury (McPherson et al. , 2019) and a reduction in knee function (Anderson et al. , 2016). However, Ardern et al. (Ardern et al. , 2011a) reported that, despite obtaining what was considered normal strength values, defined as limb symmetry index ≥80% for both knee extensor and flexor peak torque, the rate of return to pre-injury competitive level was low. This suggests that evaluating maximal strength using uni-articular, open chain assessment modes at low velocities only (the most frequently used test criteria to return athletes to unrestricted sports activities (Burgi et al. , 2019a)), does not provide a global evaluation of the relevant physical capacities needed to return to competitive sport.

Similarly, current evidence indicates a lack of consistency in the ability of functional measures commonly used to determine readiness to RTS (such as hop testing) to predict successful outcomes following ACL reconstruction. This is true for both returning to previous performance levels, and identifying those at a greater risk of re-injury (Davies et al. , 2019). Indeed, there is some evidence to suggest that passing RTS criteria significantly decreases the risk for graft rupture (Kyritsis et al. , 2016, Webster and Hewett, 2019). Conflicting findings have also been published reporting scarce or no association between passing RTS criteria and risk of a second ACL injury (Losciale et al. , 2019b). This emphasizes the need for further research and examination of a wider range of physical performance capacities that may more accurately determine an individual's state of readiness to re-perform.

Despite an increased use of functional testing, time post-surgery remains the most commonly used determinant of when an athlete can RTS (Burgi et al. , 2019b). Current evidence based guidelines (Dingenen and Gokeler, 2017, Grindem and Arundale, 2018, van Melick et al. , 2016), advocate criteria based protocols for RTS decision making. However, there are also meaningful limitations in the existing physical performance criteria advocated. Single leg hop testing is commonly adopted for functional RTS assessment (Ardern, Webster, 2011a), with increased distances suggested to demonstrate heightened knee function. Recent studies have challenged this assumption (Davies, Myer, 2019). Furthermore, it has been shown that despite achieving symmetrical hop distances, athletes with a history of ACL reconstruction are likely to demonstrate compensatory knee kinematics and kinetics (Kotsifaki et al. , 2019). Specifically, they tend to offload their reconstructed knee, landing with shallower knee flexion angles, lower knee flexion moments and reduced knee energy transfer (Kotsifaki, Korakakis, 2019). Similarly, meaningful differences in ankle, knee, hip and trunk kinematics in both sagittal and transverse planes have been shown in athletes following ACL reconstruction in dynamic tasks (Fox, 2018, King et al. , 2018b, King et al. , 2019), even though outcome measures such as timed change of direction performance and hop distance reached the values recorded on the un-involved limb (King et al. , 2018a, King, Richter, 2018b, Marques et al. , 2019). However, the effect of heightened physical capacities on the movement strategies displayed and how they relate to an athlete's injury risk profile following ACL reconstruction remains largely unknown.

When examining between-limb difference to monitor progress and patient readiness during rehabilitation, it is also worth considering that measures of physical performance are commonly compared to the uninjured limb. However, deficits following ACL reconstruction are typically bilateral, in which the contralateral limb is weaker at the time of RTS than its pre-operative values (Wellsandt et al. , 2017b). Therefore, a limb symmetry index may overestimate knee function; thus, advocating the need to relate performances in the later stages of rehabilitation to normative values from a representative sporting population (O'Malley et al. , 2018).

Current evidence also shows that only a minority of patients pass RTS test batteries and this in part can be attributed to limitations in the scoring system. Firstly, when the requirement is to "pass" a range of tests at a set cut off, adopting multiple tests across a number of domains, this reduces the percentage of athletes who pass the whole battery by chance alone (Toole et al. , 2017, Webster and Hewett, 2019). Secondly, a battery of tests (such as the hop tests) likely measures similar constructs, which are underpinned by related physical qualities. Not passing one will likely increase the likelihood of failing the others also (Davies, Myer, 2019). Thirdly, there is no consensus on when an athlete is ready to RTS, or the optimal testing procedure to determine sport readiness (Buckthorpe, 2019).

Finally, there is a lack of research which has included longitudinal profiling of 'the athletes journey' following ACL reconstruction. Most studies have assessed a range of physical qualities prior to RTS, but have not included serial measurements during rehabilitation and/or long term follow up after RTS (Webster and Hewett, 2019). For example, cross sectional studies have reported deficits in strength (Anderson, Browning, 2016), strength ratios (Kyritsis, Bahr, 2016), rate of force development (Angelozzi et al. , 2012, Kline et al. , 2015), reactive strength (King, Richter, 2018b), and peak power (Lee et al. , O'Malley, Richter, 2018, Pratt and Sigward, 2018a) have all been documented following ACL reconstruction and they can persist for a number of years (Bourne et al. , 2019). Equally, these same attributes are widely considered important physical performance determinants in high performance sports (Lorenz and Reiman, 2011, Morin and Samozino, 2016). Monitoring the progression of physical qualities during rehabilitation will allow clinicians to examine the temporal recovery of key physical attributes required to RTS and will also assist in providing key information for the development of performance strategies that may safely accelerate RTS by targeting deficits through adaptation-led training and increasing readiness to re-perform.

1.1 Overview of thesis and chapter outlines

This thesis first included an overview of the current literature. Specifically, this included a review of fundamental physical capacities following injuries (chapter 2). Then, we narrowed our literature search and focused on the effect of ACL reconstruction on strength, rate of force development, power and reactive strength (chapter 3), and their relationships with biomechanical variables commonly seen during dynamic tasks at the later stages of rehabilitation and RTS (chapter 4). Therefore, we used our data to explore recovery patterns in strength and power characteristics of professional soccer players following ACL reconstruction at RTS relative to pre-injury baseline data and healthy matched controls (chapter 6). We then assessed how strength and reactive strength levels could affect biomechanics during the SLDJ, which is a commonly used test to determine physical readiness following rehabilitation (chapter 7). Finally, we analysed how a composite score including strength, power, and reactive strength characteristics could inform RTS readiness and subsequent injury risk (chapter 8). See Figure 1.1 which provides and illustration of sequential flow of studies included in the thesis.

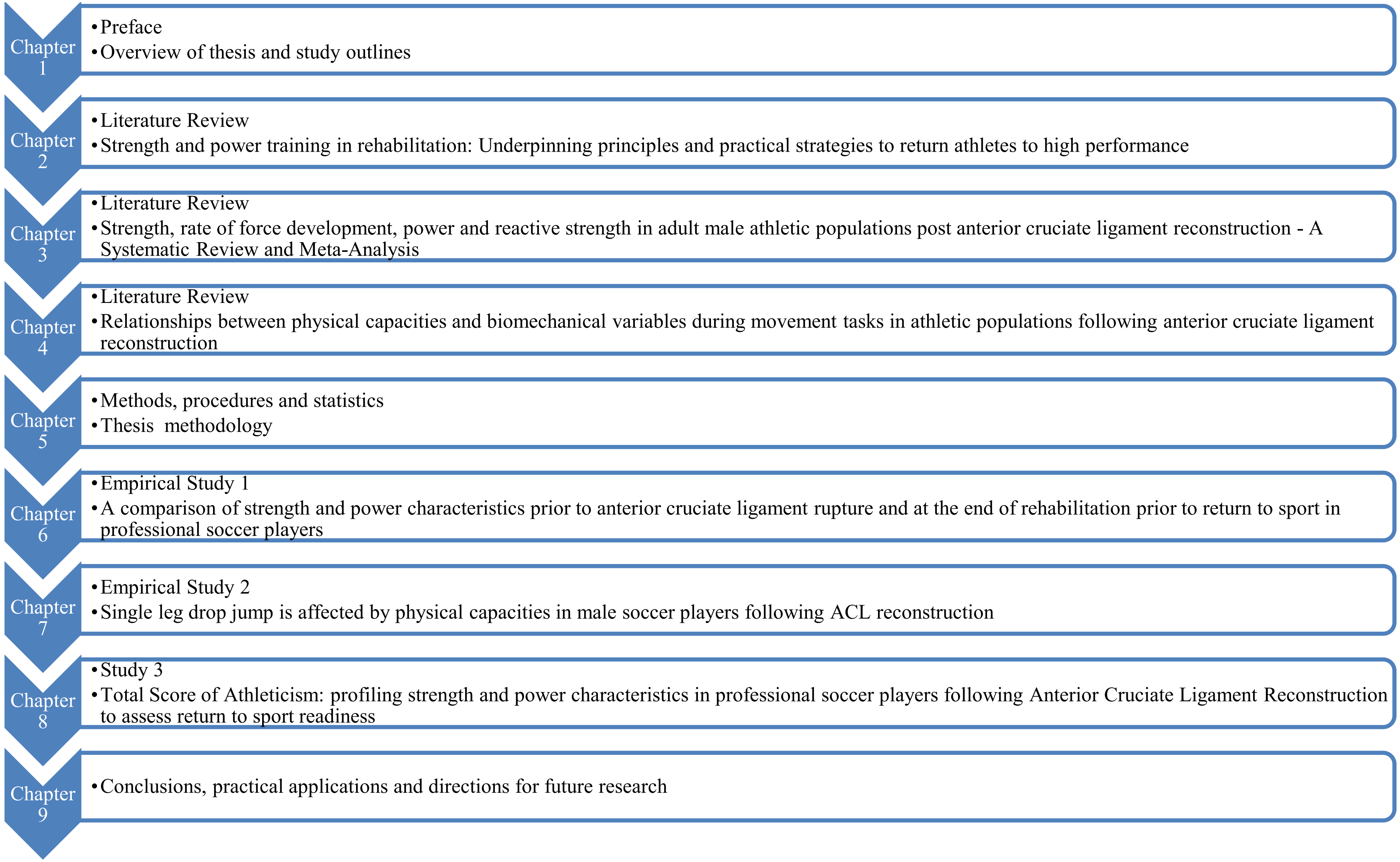

Figure 1.1 - Schematic overview of chapters in this thesis.

CHAPTER 2: LITERATURE REVIEW

Strength and power training in rehabilitation: Underpinning principles and practical strategies to return athletes to high performance

This chapter provides an overview of the shared underpinnings between injuries, rehabilitation and sports performance in general, and was not limited to ACL reconstruction, which was then selected as the targeted research area for our project. This review was published in Sports Medicine Journal (Maestroni et al. , 2020)

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2.0 Introduction

Following the occurrence of injury or pain onset, deficits in strength (Anderson, Browning, 2016, Bourne et al. , 2017, Delahunt et al. , 2017, Neal and Lack, 2018, O'Neill et al. , 2016), strength ratios (Thorborg et al. , 2014), rate of force development (Angelozzi, Madama, 2012, Cobian et al. , 2017, Kline, Morgan, 2015, Nunes et al. , 2017, Opar et al. , 2013, Wang et al. , 2011), reactive strength (Doherty et al. , 2016, Doherty et al. , 2015, King, Richter, 2018b), leg stiffness (Debenham et al. , 2016, Gore and Franklyn-Miller, 2018, Lorimer and Hume, 2016, Maquirriain, 2012, Pruyn et al. , 2012), and peak power (Lee, Yang, O'Malley, Richter, 2018, Pratt and Sigward, 2018a), have all been shown in athletic populations. Equally, these same attributes are widely considered important physical performance determinants in high performance sport (Lorenz and Reiman, 2011, Morin and Samozino, 2016). In spite of this, rehabilitation programmes often adopted in research and clinical practice are mainly focused on restoring strength (Beyer et al. , 2015, Lack et al. , 2015, Macdonald et al. , 2018, Presland et al. , 2018b), which by definition, consists of high forces at low velocities. However, this alone may not fully prepare the musculoskeletal system to accept and produce moderate to high loads at rapid velocities, which underpin most sporting actions. Furthermore, maximal strength and ballistic power training (which is typically advocated for the latter) induce different physiological adaptations. There is, however, a strong interplay and overlap in both performance and physiological determinants between maximal strength development and ballistic power training. Maximal strength serves as the foundation for the expression of high power outputs, making the adoption of training with heavy loads advantageous, not only for relatively weaker athletes, but also for improving physiological features necessary for high velocity actions (Kawamori and Haff, 2004, Newton and Kraemer, 1994). Strength training with heavy loads (i.e., ≥ 80% one repetition maximum (1RM)) increases neural drive, intermuscular coordination, myofibrillar cross-sectional area (CSA) of Type II fibers, lean muscle mass, and pennation angle (Cormie et al. , 2010, Suchomel et al. , 2018). Ballistic power training is more specific in increasing maximal power output, rate of force development (RFD), movement velocity, jump height and sprint performance via lowered motor unit recruitment thresholds, improved motor unit firing frequency, and synchronization, as well as enhanced intermuscular coordination (Cormie, McGuigan, 2010, Rodríguez-Rosell et al.). These positive physiological and performance changes are relevant from both a rehabilitative as well as performance perspective and should lead towards a unified vision that encompasses robustness and resilience for enhanced performance and reduced risk of re-/ subsequent injury.

This chapter will examine the available literature pertaining to strength and power development to provide a theoretical framework, from which, clear strategies are developed to indicate how these principles and training modes can be incorporated into rehabilitation, optimizing the return to play and return to performance process. The aim of this chapter is to give clinicians guidance with clear practical applications to assist with resolving persistent deficits that may be present in athletic populations following injury. This information is important as it will enhance sports performance and reduce the risk of recurrence and subsequent injury.

2.1 Maximal Strength

The development of muscular strength can be broadly divided into morphological and neural factors (Cormie et al. , 2011a). The maximal force generated by a single muscle fibre is directly proportional to its cross-sectional area (CSA) (Hornsby et al. , 2018, Taber et al. , 2019) which is determined by the number of sarcomeres in parallel, an important parameter of its force generating capacity. Greater pennation angles are more common in hypertrophied than in normal muscles. Maximal force is also influenced by the muscle fibres composition (Cormie, McGuigan, 2011a, Haff and Stone, 2015, Hughes et al. , 2017a, Suchomel, Nimphius, 2018). Specifically, type II fibres (IIa/IIx) have a greater capacity to generate power per unit CSA, than the relatively smaller type I fibres. Architectural features such longer fascicle length allow more force production through an optimal length-tension relationship (Cormie, McGuigan, 2011a). The number of sarcomeres in series influences a muscle's contractility and the rate at which it can shorten. In regards to neural factors, the size principle dictates that motor unit (MU) recruitment is related to motor unit type and that MUs are recruited in a sequenced manner based on their size (smallest to largest) (Henneman et al. , 1965). Thus, the availability of high-threshold MUs and/or lower threshold of MU recruitment is advantageous for higher force production. Furthermore, a higher rate of neural impulses (firing frequency) and the concurrent activation of multiple motor units (motor unit synchronization) enhance the magnitude of force generated during a contraction. These, together with an effective inter-muscular coordination (i.e. appropriate magnitude and timing of activation of agonist, synergist and antagonist muscles) permit maximal force production (Clark et al. , 2014, Cormie, McGuigan, 2011a, Haff and Stone, 2015, Hughes, Ellefsen, 2017a, Suchomel, Nimphius, 2018).

2.1.1 The importance of maximal strength

In sport, the ability to generate maximal force is limited by the time constraints of specific tasks; thus, rate of force development (RFD) and power, are a critical part of optimising physical performance. Maximal strength can be defined as the upper limit of the neuromuscular system to produce force (Stone et al. , 2004), with increases in this capacity correlated with RFD and power (Aagaard et al. , 2002, Haff and Nimphius, 2012, Rodríguez-Rosell, Pareja-Blanco, Taber et al. , 2016). Current literature suggests that athletes who can back squat 2 x body mass are able to best capitalise on these associations (Haff and Nimphius, 2012), as well as changes in endocrine concentrations (namely testosterone) in response to training (Crewther et al. , 2012). Furthermore, current evidence suggests that until athletes can squat at least 1.6 x body mass, maximal strength training should be the dominant training modality (Cormie, McGuigan, 2010). Specifically, Cormie et al. (Cormie, McGuigan, 2010) examined the effect of a 10-week (3/week) training intervention of either strength training or ballistic-power training on jumping and sprinting performances, force-velocity profile, muscle architecture, and neural drive in a cohort of 24 male subjects who were proficient in the back squat. They found that despite both groups displaying similar improvements in performance, relatively weak men (back squat < 1.6 x BM) benefited more from strength training due to its potential long-term improvement. This occurred as a result of increased neural activation and muscle thickness, which are adaptations specific to this type of training stimulus. This is in line with the recent research performed by Comfort et al. (Comfort and Thomas, 2018) who showed that prior identification of athletic physical characteristics (here using the dynamic strength index calculation) may improve the prediction of significant changes in response to a specific type of training. In particular, they emphasized the importance of increasing force production via strength training in weaker athletes. This is reinforced by James et al. (James et al. , 2018), who revealed that the magnitude of improvement in peak velocity in response to ballistic training was significantly influenced by baseline strength levels in the first 5 weeks of training. Overall, the available evidence suggests that achieving and maintaining a high level of strength is of utmost importance in the athletic population for positive adaptations.

Indeed, developing maximal strength has been shown to have significant benefits on musculotendinous stiffness (Bohm et al. , 2015), neuromuscular inhibition (Kidgell et al. , 2017, Suchomel, Nimphius, 2018), and connective tissue strength (Goodman et al. , 2015, Grzelak et al. , 2012, Magnusson and Kjaer, 2018, Watson et al. , 2018), culminating in decreases in the relative force (% of maximum) applied during the loading phase of running at ground contact (Ploutz et al. , 1994a, Ploutz et al. , 1994b, Stone et al. , 2007). Collectively this reduces metabolic demand for the same force output, creating a motor unit reserve available for additional work (Stone, Stone, 2007). Normative data to ensure when a patient or an athlete is “strong enough” are available for isometric bilateral adductor strength tests (Delahunt, Fitzpatrick, 2017, Esteve, Rathleff, 2018), although strength ratios between muscle groups of the same limb (Baroni et al. , 2018, Thorborg, Branci, 2014) or threshold for inter-limb asymmetries are more commonly reported (Adams et al. , 2012b, Ardern et al. , 2016, Bourne et al. , 2015, Bourne, Timmins, 2017, Grindem et al. , 2015, Grindem et al. , 2016, Kyritsis, Bahr, 2016). These values may be used to examine single joint strength and guide training programs, and to determine readiness to return to play following injuries; however, global measures of maximal strength are also warranted which display heightened transfer to athletic performance.

In addition to the physiological and performance advantages of developing maximal strength, it is not surprising that injury risk may be reduced by the adoption of this training modality. Lauersen et al. (Lauersen et al. , 2014b) indicated that a variety of strength training modalities can reduce sports injuries by one third, and overuse injuries by almost half. Furthermore, strength training programmes appears superior to neuromuscular training and multicomponent programmes in injury reduction (Lauersen, Bertelsen, 2014b) . More recently, Malone et al. (Malone et al. , 2019), have shown that over two consecutive seasons, athletes who are stronger, faster, and have better repeated sprint ability (RSA) times, have a lower injury risk than their weaker counterparts. Thus, increasing strength is a key component of any tertiary prevention approach and should be targeted within injury rehabilitation to reduce the risk of re-injury(Jacobsson and Timpka, 2015). However, while research and clinical practice promote increases in strength, this has been largely investigated in several injury types in isolation, often with much lighter loads and subsequently higher repetition ranges. For example, loading schemes of < 80% 1RM are often reported in research articles with a rep-set configuration of "15x3" or "10x3" without a clear indication of the load employed (Holden and Barton, 2018, Holden et al. , 2018), or by using relatively low loads, thus not targeting higher threshold motor units to maximise strength adaptations (Ishoi et al. , 2016, Malliaras et al. , 2013, Murphy et al. , 2018, Yousefzadeh et al. , 2018). Instead, the clarity in details of exercise prescription is fundamental to define the physical as well as athletic adaptations targeted.

2.1.2 Strength deficits following injury

Increased inhibitory inputs may reduce the extent to which muscles are voluntarily activated(Sonnery-Cottet and Saithna, 2019). It is widely acknowledged that in the acute phase after an injury, local phenomena occurring in peripheral tissues such as swelling, inflammation and joint laxity, may change the discharge of sensory receptors, which causes neuromuscular inhibition. This is often referred to as arthrogenic muscle inhibition after distension or damage to structures of a joint (Hopkins and Ingersoll, 2000). Neuromuscular inhibition can persist even in absence of effusion or pain (Rice and McNair, 2010), leading to persistent strength deficits that impair normal physical function, return to full performance, and increase the risk of re-injury and subsequent injury (Pietrosimone et al. , 2015). Mechanisms for this inhibition include complex neural adaptations from spinal reflex (affecting the group I non-reciprocal (Ib) inhibitory pathway, the flexion reflex and the gamma loop) and corticomotor excitability pathways (Chang et al. , 2018, Rice and McNair, 2010, Roy et al. , 2017, Te et al. , 2017). Neuromuscular inhibition would therefore explain persistent neuromuscular alterations (e.g. shift in joint-torque angle relationship, atrophy, reduction in in-series sarcomeres) and limit positive muscle adaptations to training despite the return to play (Brockett et al. , 2004, Fyfe et al. , 2013, Roig et al. , 2009, Silder et al. , 2008).

Knee extensor and flexor strength is significantly reduced after anterior cruciate ligament reconstruction (ACLR) (Anderson, Browning, 2016), even up to 10 years post-surgery (Bourne, Bruder, 2019). These measures have been used to guide rehabilitation status (O'Malley, Richter, 2018) and reported as a significant predictor of re-injury (Grindem, Snyder-Mackler, 2016). Similarly, several studies have indicated that lower levels of eccentric knee flexor strength increased the risk of hamstrings re-injury (Bourne, Timmins, 2017). This may be due to the directional specificity of the hamstring complex, or this persistent maladaptive feature not being completely resolved in previously injured players. In fact, Brughelli et al. (Brughelli et al. , 2010) showed that Australian Rules Football players with previous hamstring injuries had significant deficits in horizontal but not vertical force during running at submaximal velocities. Similarly, Lord et al. (Lord et al. , 2018) demonstrated that horizontal force production decreases at a greater rate in previously injured than uninjured hamstrings during an RSA test in football players. Charlton et al. (Charlton et al. , 2018) found isometric knee flexion strength deficits in semi-professional Australian Rules Football players with a past history of hamstring injury for up to three seasons following injury. Other studies investigating common lower limb injuries revealed discrepancies in the association between strength values and risk of injury (O'Malley, Richter, 2018, Rathleff et al. , 2014) as well as inconsistent patterns of strength and performance change in symptomatic and asymptomatic subjects (Rio et al. , 2016a). In addition, research has shown that muscle strength is impaired bilaterally and below normative data in runners with Achilles tendinopathy (O'Neill et al. , 2019).

2.1.3 Using maximal strength training to target deficits

The available data suggest higher strength levels help reduce the risk of sports injuries (Bourne, Timmins, 2017, Lauersen et al. , 2014a, Thorborg, 2012). From a rehabilitation perspective, patients should be gradually progressed to heavier loads in a periodized manner, with high-intensity resistance training being a valid and effective therapeutic tool across age and gender in the treatment of the most common musculoskeletal injuries (Booth et al. , 2017, Kristensen and Franklyn-Miller, 2012). From a neurobiological perspective, it may also reverse alterations in intra-cortical inhibitory networks in individuals with persistent musculoskeletal pain (Chang, O'Connell, 2018, Rio, Kidgell, 2016a, Roy, Bouyer, 2017).

Current evidence indicates that prescription of maximal strength training should involve a load (or intensity) of 80-100% of the participant's one-repetition maximum (1-RM), utilizing approximately 1-6 repetitions, across 3-5 sets, with rest periods of 3-5 minutes and a frequency of 2-3 times per week (2009). Hence, for clinicians whose specific aim at a particular phase is to improve maximal force, they should be progressively working toward this volume load prescription. Evidence-based recommendations for an effective stimulus for tendon adaptation suggest high intensity loading (85–90% iMVC) applied in five sets of four repetitions with a contraction and relaxation duration of 3 s each and an inter-set rest of 2min (Mersmann et al. , 2017). However, in the initial stages when they are unable to tolerate heavy loads, lower intensities may be employed in multiple high volume sets until momentary failure, in order to recruit the highest threshold motor units and to increase CSA (Schoenfeld et al. , 2018, Schoenfeld et al. , 2017). Alternatively, blood flow restriction training can be used to provide an effective stimulus during rehabilitation for patients who are load compromised (Hughes et al. , 2017b). Cross-education (i.e. heavy resistance training of the unaffected limb) can be also a viable option to reduce corticospinal inhibition (Kidgell et al. , 2015), to increase contralateral limb strength (Cirer-Sastre et al. , 2017) and to induce hypoalgesia (Vaegter, 2017). A potential progression based on the rehabilitation phase and the patient's irritability post ACLR might be: 1) bodyweight single leg squat performed at high volume sets focusing on technique mastery and cross-education 2) single leg squat with light load and high volume sets until failure (with/without blood flow restriction) 3) split squat with progressive loading in a traditional periodization scheme until reaching the recommended prescription for maximal strength 4) split squat performed accordingly with maximal strength recommendations, with potential adaptations highlighted in Table 2.1.

Table 2.1 Examples of different resistance training prescriptions to enhance strength are included in the table. The assigned exercises are ordered from the lowest to the highest intensity. Potential physiological and performance adaptations are also listed.

Example of targeted muscle group	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**	**Stage 5**
Quadriceps	Isometric leg extension 45” x 5 reps @60° knee flexion and @>80%1RM	Isotonic leg extension 5 sets x until failure	Split squat 3-6 reps x 2-6 sets @85–93%1RM	Eccentric single leg box squat 3-6 reps x 2-6 sets @110-120% 1RM	Contrast approach - Trap bar deadlift 4RM paired with triple hop x 4 sets
Possible performance gains	↑ Peak Power ↑ Strength ↑ RFD ↓ Inter-limb asymmetries ↑ Horizontal force production ↑ Vertical force production				

RM (repetition maximum), ↑(increased), ↓(decreased), →(unchanged)

2.1.4 Using isometric strength training to target deficits

From a rehabilitation perspective, isometric contractions may be employed during specific phases where dynamic contractions may be contraindicated. Although dependent on the persistent musculoskeletal condition analysed, isometric contractions are capable of inducing hypoalgesia for chronic hand, knee, and shoulder injuries (Naugle et al. , 2012), also during in-season (Rio et al. , 2017, Rio et al. , 2016b). The hypoalgesic effect is however, variable and not always consistent (O'Neill et al. , 2018, Riel and Vicenzino, 2018). This may depend on the population analysed, the tissues properties, the physical activity level, and the pain modulation profile of the subjects assessed (Coombes and Tucker, 2018, Lemley et al. , 2015, Naugle et al. , 2014, Naugle et al. , 2017, Sluka et al. , 2018).

During isometric contractions, the muscle-tendon unit remains at a constant length. Isometric muscle actions have been widely used due to their tightly controlled application of force at specific joint-angles, their ability to develop greater force than concentric contractions, and their high reliability in assessing and tracking force production (Oranchuk et al.). Isometric training at long muscle lengths and at high volumes are more effective for inducing muscle hypertrophy than at short muscle lengths (Alegre et al. , 2014, Kubo et al. , 2006, Noorkoiv et al. , 2014), potentially due to greater blood flow occlusion, rates of oxygen consumption, and metabolite build-up (de Ruiter et al. , 2005). Although it may not be an effective strategy for directly improving sports performance, isometric training shows the largest improvements at the trained angles (Oranchuk, Storey). This has connotations for athletes who are rehabilitating following injury. For example, in ACL deficient subjects, angle specific quadriceps muscle torque between-limb deficits were more evident at angles of less than 40 degrees knee flexion as opposed to the peak torque recorded during the trial (not considering the angle at which this occurred) (Eitzen et al. , 2010, Huang et al. , 2017). This may reveal the potential utility of implementing positional isometrics in a rehabilitation programme for ACL deficient patients. Similarly, isometric quadriceps muscle actions, using the leg extension machine at 80% of the MVIC, and holding for 45 seconds for 5 sets, with one minute between sets, may be employed for subjects with patellar tendinopathy when isotonic contractions are not tolerated or during in season (Rio et al. , 2015, Rio, Purdam, 2017, Rio, van Ark, 2016b).

2.2 Rate of Force and Torque Development

2.2.0 The importance of rate of force development

Rate of Force Development (RFD) is defined as the ability of the neuromuscular system to produce a high rate of rise in muscle force per unit of time during the initial phase following contraction onset (Rodríguez-Rosell, Pareja-Blanco); torque refers to a force that causes rotation. Contractile RFD is a parameter used for measuring “explosive” strength capabilities. It is determined from the slope of the force time curve (generally between 0 and 250 milliseconds), and calculated as ΔForce/ΔTime. Several factors can impact RFD, particularly the early phase (< 100 ms relative to contraction onset), which is more influenced by intrinsic muscle properties and neural drive, while the late phase (>100 ms relative to contraction onset) is more respondent to maximal muscle strength (Maffiuletti et al. , 2016, Rodríguez-Rosell, Pareja-Blanco). Considering that force application during skills such as sprinting, jumping, throwing, and kicking last approximately 30–200 milliseconds (Taber, Bellon, 2016), RFD is a critical performance characteristic central to success in most power-based sporting events, as well as endurance running performance (Brazier et al. , 2017).

2.2.1 RFD deficits following injury

In addition to the short time frames available to execute sporting tasks, it has been demonstrated that non-contact ACL tears occur in a timeframe of less than 50 milliseconds, while the quadriceps, for example, requires more than 300 milliseconds to reach peak torque during isometric testing (Kline, Morgan, 2015). Angelozzi et al. (Angelozzi, Madama, 2012) found significant deficits in RFD at six months post–ACLR in professional soccer players who had completed a typical standardized rehabilitation program and achieved nearly full recovery in the International Knee Documentation Committee (IKDC), Tegner activity scale, KT1000 and MVIC, which are objective measures commonly used to guide return to sports decision making. Similarly, Kline et al. (Kline, Morgan, 2015) demonstrated reduced quadriceps RFD in subjects at six months post ACLR with patellar tendon autograft.

Deficits in RFD have also been shown in other common pathologies. For example, Nunes et al. (Nunes, Barton, 2017) found reduced RFD in hip abduction and extension in a cohort of physically active females with patellofemoral pain. In addition, Wang et al. (Wang, Lin, 2011) demonstrated lower values in early RFD in the triceps surae muscle in elite athletes with unilateral chronic Achilles tendinopathy, while Opar et al. (Opar, Williams, 2013) showed lower rate of torque development in previously injured hamstrings. Cumulatively, the available evidence indicates that restoration of the ability to apply high forces in short time frames is crucial from both a rehabilitative and performance perspective.

2.2.2 Using training to target RFD deficits

The available evidence indicates that training at high velocities or with the intention to move loads quickly, is highly effective in eliciting marked gains in rapid force production capacity (Andersen et al. , 2010, Balshaw et al. , 2016, Maffiuletti, Aagaard, 2016, Tillin et al. , 2012). This includes medicine ball throws, plyometrics (Butler et al. , 2003a), Olympic weightlifting and their derivatives (Haff and Nimphius, 2012, Suchomel et al. , 2017) (see Table 2.2 for further examples). The prescription of these can be best appreciated by defining the mechanical parameters that underpin power. Mechanically, power is the work performed per unit of time, or force multiplied by velocity. The inverse relationship between force and velocity can be illustrated by the force-velocity (FV) curve (Figure 2.1), which identifies that maximum strength is exerted under high loads, and maximum speed is produced under low loads (Taber, Bellon, 2016). Subsequently, the goal of strength and conditioning programming is to improve force capability under the full spectrum of loads and thus velocities. For example, emerging evidence shows how different force-velocity profiles exist within individuals; thus, suggesting that improving maximal strength may be most beneficial for some athletes, while others may benefit most from improving force at high velocity (Jiménez-Reyes et al. , 2016, Suchomel, Comfort, 2017). This has been shown recently by Jimenez-Reyes et al. (Jiménez-Reyes, Samozino, 2016) who tailored the training programme based on the Force-Velocity profile during jumping. An individualized training programme specifically based on the difference between the actual and optimal Force-Velocity profiles of each individual (F-V imbalance) was more effective in improving jumping performance than traditional resistance training common to all subjects (velocity-deficit, force-deficit, and well-balanced increased by 12.7 ± 5.7% ES=0.93 ± 0.09, 14.2 ± 7.3% ES=1.00 ± 0.17, and 7.2 ± 4.5% ES=0.70 ± 0.36, respectively). Furthermore, despite being just a case report, Mendiguchia et al. found that the capability to produce horizontal force at low speed (FH0) was altered both before and after return to sport from a hamstring injury in two professional athletes; thus, changing the slope of the F-V relationship (Mendiguchia et al. , 2016). The data collectively show that athletes need a well-rounded approach that prepares them to tolerate high and low loads as well as high and low velocities, not only from a performance perspective, but also to empower resilience to different stress stimuli and to increase musculoskeletal robustness.

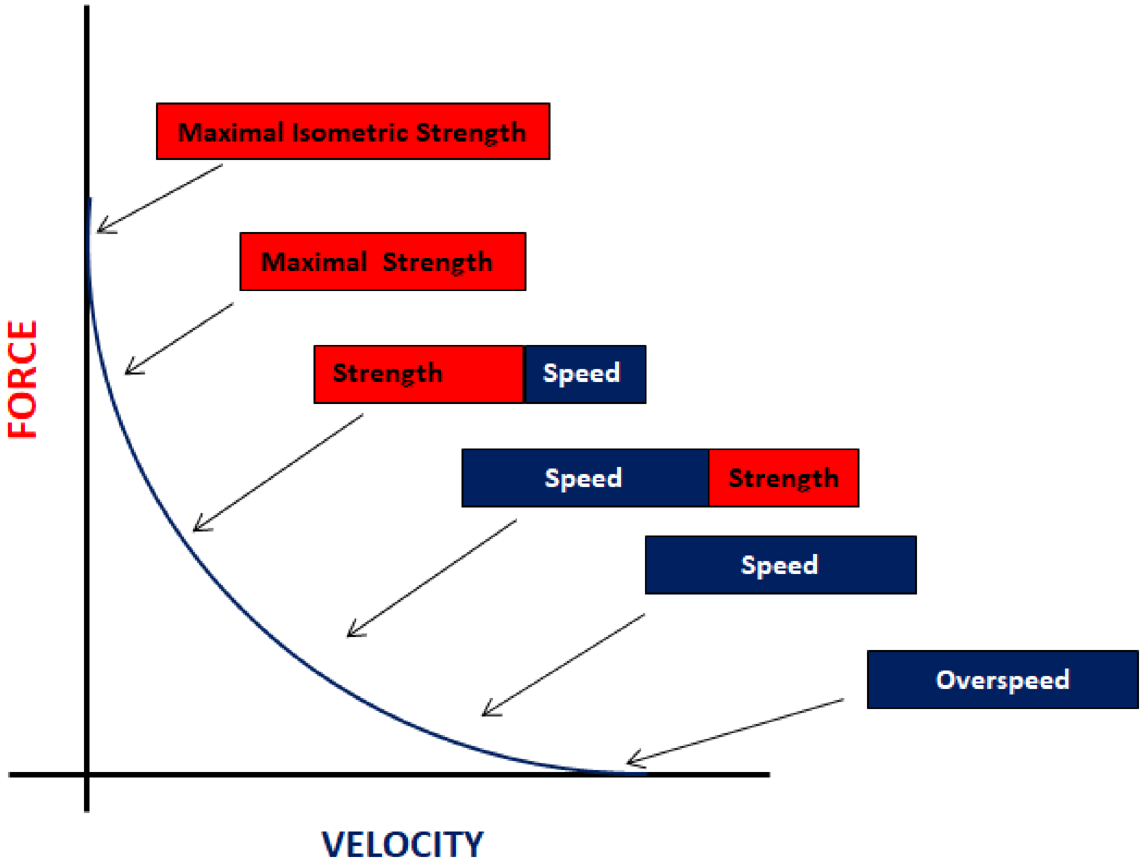

Figure 2.1 Concentric portion of the Force-Velocity curve

Table 2.2 Examples of exercises aiming to enhance RFD via ballistic/power are included in the table. Potential physiological and performance adaptations are also listed.

Example of prescriptions	Example 1	Example 2	Example 3	Example 4
	Squat jumps (start position from static pause) 3 x 5 sets	Jump shrug 3 x 4 sets (30 to 45% 1RM of the Hang Clean)	Single leg countermovement jump 4 x 4 sets (w/ variable loads)	Explosive contractions (10 isometric contractions "as fast and hard as possible" x 4 sets)
Possible performance gains	↑ Peak Power ↑ CoD performance ↑ Early/Late RFD ↑ Speed ↑ Jump Performance ↓ Inter-limb asymmetries ↑ Running Economy			

RM (repetition maximum), ↑(increased), ↓(decreased)

2.3 Reactive Strength

2.3.0 The importance of reactive strength

Eccentric actions are those in which the musculotendinous unit actively lengthens throughout the muscle action. Eccentric training has received considerable attention due to its potentially more favourable adaptations compared to concentric, isometric, and traditional isotonic (eccentric/concentric) training (Aagaard, 2018, Nishikawa, 2016). These include superior benefits for isometric and concentric strength, preferential recruitment of type II muscle fibers, power, RFD and stiffness, muscle architecture, and increased muscle activation, as well as improved performance in sporting actions (Harden et al. , 2018, Suchomel, Nimphius, 2018, Wagle et al. , 2017). Forceful eccentric contractions may have a superior impact in reducing intra-cortical inhibition and in increasing intra-cortical facilitation (Kidgell, Frazer, 2015, Tallent et al. , 2017). These improvements can occur where there are high eccentric stretch-loads, such as landing and change of direction mechanics, and fast stretch-shortening cycle (SSC) demands, because an athlete's reactive-strength ability is underpinned by relative maximal eccentric strength (Beattie et al. , 2017); this again reinforces the need of substantial high levels of strength values before developing SSC capabilities (James, Gregory Haff, 2018). The reactive strength index (RSI) has been widely employed to quantify plyometric or SSC performance, that is the ability to change quickly from an eccentric to concentric muscle action (Flanagan and Comyns, 2008). The factors that underpin an efficient SSC are related to the storage and the reutilization of elastic energy. These are the result of a number of mechanisms including utilization of intrinsic muscle-tendon stiffness, involuntary reflex muscle activity, antagonistic co-contraction, and the SSC pre-stretch (Pedley et al. , 2017). The latter, referred also as pre-activation during the eccentric phase, may allow for a greater number of motor units to be recruited during the concentric contraction through neural potentiation, thus indicating the important role of eccentric force production in SSC capabilities (Flanagan and Comyns, 2008, McBride et al. , 2008).

The RSI can be used to assess leg stiffness. This can be described as the resistance to the deformation of the lower limb in response to an applied force. Therefore, a certain amount of lower extremity stiffness is required for effective storage and re-utilization of elastic energy in SSC activities (Brazier, Maloney, 2017). Lower extremity stiffness is considered to be a key attribute in the enhancement of running, jumping and hopping activities (Asadi et al. , 2016, Lum et al.). Indeed, numerous studies reported that lower extremity stiffness increases with running velocity and this is concomitant with increased vertical ground reaction forces (GRFs), increased ground contact frequency, and shorter ground contact times (Butler et al. , 2003b, McBride, McCaulley, 2008). SSC activities have been divided into fast SSC (<250ms) and slow SSC (>250ms) accordingly with the ground contact time.

2.3.1 Reactive strength deficits following injury

Emerging evidence shows the importance of incorporating drop jumps in the evaluation of RSI as criteria for return to play. King et al. (King, Richter, 2018b) revealed that the single leg drop jump identified greater performance deficits between the ACL reconstructed limb and the non-operated limb compared to the single leg hop for distance, suggesting insufficient rehabilitation status at nine months post-surgery. Incomplete restoration of reactive strength and stiffness capabilities may also be present in the periods following a range of other injuries. Gore et al. (Gore and Franklyn-Miller, 2018) found that hip abductor stiffness was impaired in a cohort of subjects with athletic groin pain compared to controls and that this difference was no longer significant after the rehabilitation period. In the presence of Achilles Tendinopathy, several studies have shown that the tendon mechanical properties (Child et al. , 2010, Obst et al. , 2018), modulations of the SSC, leg stiffness, and RFD are altered (Debenham, Travers, 2016, Maquirriain, 2012, Wang, Lin, 2011). This is in contrast with the normal function of the tendon complex, whose key role is to store, recoil and release energy while maintaining optimal efficiency in power production (Turner and Jeffreys, 2010).

2.3.2 Using training to target reactive strength deficits

Attainment of an adequate strength level is fundamental to the development of reactive strength as discussed previously. In addition, plyometric training can enhance early and late RFD as well as optimizing leg stiffness and the modulation of the SSC (Haff and Nimphius, 2012, Maloney et al. , 2019). Plyometric training exploits the rapid cyclical muscle action of the SSC whereby the muscle undergoes a lengthening movement ("eccentric muscle action"), followed by a transitional period prior to the shortening movement ("concentric contraction") and can be used to improve eccentric force generation capacity. Flanagan et al. (Flanagan and Comyns, 2008) suggested a 4 step progression focusing on the eccentric jumping action while landing (phase 1); rebound spring like actions with short ground contact times (phase 2); hurdle jumps with an emphasis on short ground contact while increasing intensity of the eccentric stimulus (phase 3); and finally depth jumps in order to maximise jump height while maintaining minimal ground contact times (phase 4) (Table 2.3). Furthermore, progressive training intensities might be an effective prescription to achieve improvements in change of direction ability (Asadi, Arazi, 2016, Maloney et al. , 2017).

Alternative strategies for athletes who have attained the requisite level of strength include accentuated eccentric loading (AEL) to increase eccentric strength via supra-maximal loading (Aagaard, 2018, Beattie, Carson, 2017). Examples include adopting weight releasers or dumbbells dropped in the bottom position in order to overload the eccentric portion of the movement, enhancing the subsequent concentric action. Patients post ACLR who are a substantial time period from their surgery and have reached normative strength values across different ranges of motion and velocities, may benefit from AEL to further increase quadriceps eccentric strength (Lepley and Palmieri-Smith, 2013), together with progressive intensities of plyometric training. However, AEL by definition is not commonly employed in rehabilitation strategies, although sports medicine professionals are now widely applying eccentric loads for the prevention and rehabilitation of hamstring injuries. The Nordic hamstring exercise has been shown to significantly reduce the risk of hamstring injuries (Arnason et al. , 2008, Petersen et al. , 2011, van der Horst et al. , 2015). Furthermore, even a low training volume can stimulate increases in fascicle length and improvements in eccentric knee flexor strength (Presland et al. , 2018a). Similarly, the Copenhagen adduction exercise is commonly prescribed due to its superior ability to increase eccentric hip adduction strength (Ishoi, Sorensen, 2016) and the eccentric triceps surae exercise has been shown not only to increase maximal strength, tendon stiffness, Young's modulus and tendon CSA (Bohm, Mersmann, 2015, Geremia et al. , 2018, Mersmann, Bohm, 2017), but also ankle dorsiflexion (Aune et al. , 2018) and the SSC behaviour.

Practically, AEL can be applied by completing the concentric portion of the movement with both limbs at high loading schemes and by using only the involved limb for the eccentric portion, thus resulting in load above 100% of 1RM. Similarly, the athlete may also be assisted during the concentric portion of the exercise while the eccentric portion is completed independently. Alternatively, the use of heavy chains allows increases of load during both the early concentric phase of the lift as well as early eccentric phase of the descent, due to the favourable muscle leverage and the additional chain links (Ghigiarelli et al. , 2009).

Table 2.3 Example of plyometric exercises to improve SSC capabilities. The assigned exercises are ordered from the lowest to the highest intensity. Potential physiological and performance adaptations are also listed.

Example of prescriptions	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**
	Drop lands 6reps x 8sets	Pogo jumps 8 contacts x 8 sets	Skipping rope 15 contacts x 5 sets	Drop vertical jumps 5 x 3 sets (from a 30cm box)
Possible performance gains	↑ Eccentric strength ↑ Peak Power ↑ CoD performance ↑ Early RFD ↑ RSI ↑ Jump Performance ↓ Inter-limb asymmetries ↑ Running Economy ↓ Ground Contact Time			

↑(increased), ↓(decreased)

2.4 Return to play tests and the need to test multiple physical capacities

A recent review on the topic of ACL rehabilitation summarised that there is a high rate of return to sport overall (81%-82%) but a lower rate for competitive sports (44%-55%). These data appear to be dictated by fear of re-injury as well as functional capabilities of the reconstructed knee; the latter tended to be deemed optimal when both Limb Symmetry Index and hop tests reach at least 90% of the contralateral limb (Anderson, Browning, 2016). However, Ardern et al. (Ardern, Webster, 2011a) found that, despite obtaining what was considered normal strength values, the rate of return to sport was low. This suggests that evaluating maximal strength at low velocities only, as per current most common criteria to return athletes to unrestricted sports activities, is not sufficient. Indeed, a recent review (Burgi, Peters, 2019b) analysed the discharge criteria for RTS following primary ACLR in studies published from 2001 to 2011, revealing that 85% of studies used time based measures as RTS criterion. Strength criteria were reported in 41% of studies, whereas physical performance-based criteria in only 20% of studies. This may indicate a potential gap in the implementation of performance strategies and tests in rehabilitation settings. Return to play criteria should therefore also consider multiple physical capacities and assessments of maximal strength, reactive strength, RFD, and power capabilities along the whole F-V curve and in multiple planes, in addition to vertical jumps, change of directions, acceleration, deceleration and speed actions as dictated by each individual's sports demands through the completion of a comprehensive needs analysis.

2.5 Program Design

When attempting to maximize power output, provided that a high overall level of strength has been reached, a periodized mixed methods approach, in which a variety of loads and exercise types are used is suggested. This is because it allows a more complete development of the force-velocity relationship (figure 2.1). The use of low-load, high-velocity movements (such as unloaded jump squats) may have a greater influence on the high-velocity area of the force-velocity curve, while heavier loads (e.g. used in the back squat) improve to a greater degree the high-force portion (Haff and Stone, 2015). Training modalities may therefore include weightlifting exercises and/or derivatives, unilateral and/or bilateral training with a range of loads, and plyometric or ballistic exercises in an appropriately periodized manner (Comfort et al. , 2018, Haff and Nimphius, 2012, Maffiuletti, Aagaard, 2016). Optimal levels of maximal strength are the foundation for the development of efficient SSC properties, as well as for ballistic sport-specific movements. Furthermore, volume and intensity will be manipulated to maximise physical capabilities throughout their rehabilitation as dictated by their ability to load safely in the context of their injury and also as the athlete transitions towards a return to sports performance (Cunanan et al. , 2018, Kiely, 2018). Examples of potential rehabilitation programmes are outlined in Table 2.4 and 2.5.

Table 2.4 Example of exercises for Football player (midfielder) with persistent Achilles Tendinopathy presenting with maladaptive reduced triceps surae capacities aiming to full Rehabilitation and enhanced Performance over a 12 weeks period

Rehabilitation Phase	Training Aim	Exercise Prescription
Phase 1 – Work capacity/pain reduction emphasis	To increase strength-endurance and reduce pain	Unilateral seated calf raises (3 sets with manageable load until failure) Isometric calf raises on smith machine (3 x 45s) RFESS (3 x 8RM each leg)
Phase 2 – Strength emphasis	To increase muscle strength and musculotendinous stiffness	Eccentric heel drops (4 x 10) Unilateral standing calf raises (4 x 6-8RM) RFESS (4 x 6RM) Drop lands (4 x 4)
Phase 3 – Power and RFD emphasis	To increase power output and RFD	Split squat (3 x 3RM each leg) Pogos (3 x 15-20 foot contacts) Drop jumps (4 x 4 from 20cm)
Phase 4 – Peak power and RFD emphasis	To increase peak power, RFD and enhanced stiffness	Front squat (3 x 2RM) Drop jumps (5 x 3 from 40cm) Unilateral drop jumps (3 x 3 from 20cm each leg)

RM = repetition maximum; RFD = rate of force development; RFESS = rear foot elevated split squat

Table 2.5 Example of exercises for a soccer player (midfielder) at 6 months post-ACLR presenting with maladaptive reduced quadriceps capacities. The aim is to complete Rehabilitation fully and to enhance Performance over a 12-16 weeks period

Rehabilitation Phase	Training Aim	Exercise Prescription
Phase 1 – Work capacity emphasis	To increase strength-endurance of the quadriceps	Unilateral leg extension (3 sets with manageable load until failure) Single leg squat (3 sets until failure)
Phase 2 – Strength emphasis	To increase quadriceps muscle strength	Front squat (4 x 6RM) Split squat (4 x 6RM) Romanian Deadlift (4 x 6RM)
Phase 3 – Power and RFD emphasis	To increase power output and RFD	Split squat (3 x 3RM each leg) Squat jumps (3 x 4) CMJ (3 x 4) SL hop (3 x 4 each leg)
Phase 4 – Peak power and RFD emphasis	To increase peak power, RFD and enhanced stiffness	Front squat (3 x 2RM) Drop jumps (5 x 3) Repeated hurdle jumps (5 x 5) SLCMJ (5 x 3 each leg)

RM = repetition maximum; RFD = rate of force development

2.6 Conclusion

This chapter has examined persistent deficits in fundamental physical qualities, such as strength, rate of force development and reactive strength following injury. Training strategies to target these deficits have also been discussed in order to increase an athlete's readiness to return to sport. The concepts expressed in this chapter may help clinicians to reduce the gap between rehabilitation and sports performance, while providing a means of tertiary prevention following injury. Rehabilitation should not only aim to return athletes to play, but also to full or enhanced performance. To achieve this, a strong cooperation among health professionals, coaches and strength and conditioning specialists is essential. Furthermore, implementation of the best available evidence of strength and conditioning and exercise physiology is required to maximize training adaptation.

After exploring the available literature pertaining to injury and physical capacities in general, we then focused our literature search on adult male athletes at the later stages of rehabilitation and at RTS following ACL reconstruction as this was the cohort for the experimental research which follows.

CHAPTER 3: SYSTEMATIC REVIEW AND META-ANALYSIS

Strength, rate of force development, power and reactive strength in adult male athletic populations post anterior cruciate ligament reconstruction - A Systematic Review and Meta-Analysis

In this chapter we aimed to assess the level of physical capacities in adult male athletic populations at the later stages of rehabilitation and at RTS in comparison to healthy controls. This Systematic Review and Meta-Analysis was published in Physical Therapy in Sport Journal (Maestroni et al. , 2021b)

Maestroni, L., Read, P., Turner, A., Korakakis, V., & Papadopoulos, K. (2021). Strength, rate of force development, power and reactive strength in adult male athletic populations post anterior cruciate ligament reconstruction-A systematic review and meta-analysis. Physical Therapy in Sport, 47, 91-104.

3.0 Introduction

The impact of anterior cruciate ligament (ACL) injuries can include a long absence from sports, lifelong financial, socioeconomic, and emotional burdens, reduced confidence in their knee and perceived self-efficacy, in addition to early development of osteoarthritis, risk of re-injury (graft rupture) and contralateral ACL injury (Ajuied et al. , 2014, Culvenor, Collins, 2015, Czuppon et al. , 2014, Engstrom et al. , 1990, Kyritsis, Bahr, 2016, Lai, Feller, 2018b, Larsen, Jensen, 1999, Losciale, Zdeb, 2019b, O'Connor et al. , 2019). Significant deficits in muscle function have also commonly been reported following ACL reconstruction (ACLR). Specifically, reductions in quadriceps muscle cross-sectional area (CSA), tissue quality, strength, central activation ratio (CAR), and rate of torque development (RTD), which may persist for years after the completion of rehabilitation and RTS (Birchmeier et al. , 2019, Curran et al. , 2018, Garcia et al. , 2020, Herrington et al. , 2018, Jordan et al. , 2017, Kline, Morgan, 2015, Lisee et al. , 2019a, Palmieri-Smith and Lepley, 2015, Pua et al. , 2017, Thomas et al. , 2015, Ward et al. , 2018). These impairments can have detrimental implications for athletes as the ability to express high power outputs is an important performance indicator (Haff and

Stone, 2015), and force must be generated within specific time constraints. However, a synthesis of the literature to determine the magnitude of residual deficits in ACLR cohorts compared to healthy populations is needed. Recent systematic reviews and meta-analysis (Lisee et al. , 2019c, Petersen et al. , 2014) showed persistent strength deficits in the ACLR limb compared to controls. However, large heterogeneity was present in confounding variables such as gender, graft type, and level of sports participation. Furthermore, a broader examination of pertinent physical qualities such as rate of force development (RFD) and reactive strength following ACLR is required to more clearly elucidate an athlete's state of readiness to re-perform and inform the content of reconditioning programs with the aim of reducing the risk of secondary injuries.

In athletic populations, research indicates that healthy athletes who can squat 2 x body mass express higher power outputs than their weaker counterparts in vertical and horizontal jumping activities (Haff and Nimphius, 2012). Furthermore, Case et al. (Case et al. , 2020) showed that male football players displaying 1RM back squat (normalized to body mass) values below 2.2 were at higher risk for lower extremity injuries during the season in comparison to stronger individuals (ES = 0.86). Specific strength qualities, such as maximal eccentric strength underpin an athlete's reactive-strength ability and allow an efficient storage and reutilisation of elastic energy during stretch-shortening cycle (SSC) activities (Beattie, Carson, 2017, Suchomel et al. , 2019a). Greater eccentric strength, reactive strength, and leg stiffness, significantly correlate with a reduced metabolic cost of running and enhanced change of direction (COD) performance (Li et al. , 2019, Maloney, Richards, 2017). Furthermore, eccentric knee extensor and flexor strength exhibit large correlations (r > -0.603) with COD performance in female soccer players (Jones and Thomas, 2017) and male athletes (r= -0.506 and r= -0.592 for normalised isokinetic eccentric extension and flexion strength respectively) (Jones et al. , 2009). That said, pivoting, cutting, landing, and jumping sports (e.g. soccer, basketball or rugby) also expose athletes to a high risk of sustaining an anterior cruciate ligament (ACL) injury (Lindanger et al. , 2019, Moses et al. , 2012, Silvers-Granelli et al. , 2017). Thus, it seems prudent to determine an athlete's level of maximal and reactive strength in the later stages of rehabilitation to ensure they possess adequate physical capacity to safely and efficiently execute commonly performed sports skills. Higher knee extension strength limb symmetry indexes (LSI) have been associated with reduced rate of re-injury (Grindem, Snyder-Mackler, 2016), and thus are commonly considered important RTS criteria. However, Ardern et al. (Ardern, Webster, 2011a) found that these widely used RTS criteria were achieved also in cohorts with a relatively low rate of return to competitive sport, thus not being considered adequate enough to detect relevant factors for RTS success.

Due to observed time constraints in many sporting actions (e.g., COD) which limit the production of maximal force, RFD should also be assessed. Defined as the ability of the neuromuscular system to produce a high rate in the rise of muscle force in the first 30-250 milliseconds (Taber, Bellon, 2016), RFD is calculated as ΔForce/ΔTime, which is determined from the slope of the force time curve (generally between 0 and 250 milliseconds) (Maffiuletti, Aagaard, 2016, Rodriguez-Rosell et al. , 2018). This performance characteristic is central to success in most power-based sporting events (Brazier, Maloney, 2017). Impaired knee extension RTD has been reported following ACLR (Angelozzi, Madama, 2012, Pua, Mentiplay, 2017), and is associated with decreased self-reported knee function (Angelozzi, Madama, 2012, Davis et al. , 2017, Hsieh et al. , 2015). Normative values in RFD/RTD associated with readiness to RTS would represent useful additional criteria to assess rehabilitation status and to plan the athletes return to more complex ballistic tasks. In addition, comparisons to healthy controls are warranted to determine the magnitude of observed deficits as an indicator of readiness to re-perform.

Current evidence suggests that residual deficits in fundamental athletic qualities such as maximal strength and RFD are present following ACLR; however, a synthesis of the available literature to determine the effects of ACLR on these explosive strength qualities is currently unavailable. The aim of this systematic review and meta-analysis was to investigate the level of physical capacities such as strength, RFD, power and reactive strength in male adult athletic populations during the later stages (> 6 months) of rehabilitation following ACLR compared to healthy, non-injured controls.

3.1 Methods

3.1.1 Protocol

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines were followed in the preparation, conduct, and reporting of this review (Liberati et al. , 2009).

3.1.2. Eligibility criteria and information sources

The studies were selected according to PICOS framework (Participants, Intervention, Comparison, Outcome, and Study design) (Liberati, Altman, 2009). Controlled cohort studies investigating strength, RFD or reactive strength in adult males following ACLR were considered. They had to be published in peer-reviewed journals and written using English language between 2010 and April 2020. These dates were chosen after reviewing the conclusions from two systematic reviews (Narducci et al. , 2011, Thomee et al. , 2011) published in 2011, which analysed the clinical utility and predictive validity of functional performance tests after ACLR, and found a paucity of literature with regard to the critical elements that determine readiness to RTS. The examined population was male adults (>18 years) following ACLR with any graft type during the later stages of their rehabilitation (≥ 6 months post-surgery), with performance compared to matched controls. Studies assessing strength, RFD or reactive strength were considered. The outcome measures were the effect of ACLR on (1) strength; (2) RFD/power; (3) reactive strength.

3.1.3 Searches

A comprehensive literature search of three electronic databases (MEDLINE, SPORTDiscus and CINHAL) was conducted on 14 April 2020. The reference lists of articles found were also scanned. Two authors (LM and KP) developed a systematic search strategy following the PICOS framework (Liberati, Altman, 2009). The search strategy used is listed in Appendix 1. The keywords "strength" or "rate of force development" "or power" or "reactive strength" were combined with the Boolean operator "AND" for keywords pertinent to anterior cruciate ligament reconstruction (e.g. "ACLR", "ACL reconstruction")

3.1.4 Study selection

Two reviewers (LM and KP) independently screened titles and abstracts to identify relevant studies. Title and abstracts investigating ACLR adult male populations (≥ 18 years) with at least one group ≥ 6 months, which included the assessment of strength, RFD or reactive strength were considered. Full-text manuscripts of remaining eligible studies were evaluated for inclusion in this review. The additional inclusion criteria were: (1) presence of a control group; (2) patients with any ACLR graft type; (3) assessment of strength, RFD or reactive strength using dynamometers or force platforms.

Studies were excluded for the following reasons: (1) absence of a control group; (2) studies including patients <18 years; (3) patients with revision ACLR or bilateral ACL injury; (4) nonsurgical treatment of ACL injury; (5) inclusion of female patients; (6) no conventional assessment of strength (e.g. manual muscle testing), RFD or reactive strength.

3.1.5 Data extraction

Two authors (LM and KP) independently extracted data from the included studies. Disagreements regarding the selection criteria were discussed and resolved by consensus including all four authors (LM, KP, PR and AT). Demographic details including population size, gender, age, graft type, time since surgery and rehabilitation status were recorded from each study. The following variables were extracted: strength, rate of force development/power and reactive strength.

3.1.6 Assessment of level of evidence, quality, risk of bias in individual studies and across studies

The level of evidence, methodological quality and risk of bias of each individual study was examined independently by two authors (LM and KP). The Oxford Centre for Evidence-Based Medicine (OCEBM) Levels of Evidence tool was used to assess the level of evidence and quality of research design for each included study, where level 1 indicates the highest category, and Level 5 the lowest. Study quality was examined using the modified Downs and Black scale, which is a reliable tool for cohort studies (Downs and Black, 1998). The highest total score for the modified version is 16. A score ≥ 12 is considered high quality; a score of 10 and 11 are moderate quality; and a score ≤ 9 is deemed low quality (Losciale, Zdeb, 2019b). The methodological quality of the selected studies was assessed using the PEDro Scale, which considers the following characteristics: sequence generation, allocation concealment, blinding, incomplete outcome data, and selective outcome reporting.

A risk of bias assessment for each of the selected studies was conducted to identify the presence of any publication bias, selective data reporting, conflict of interest, time lag bias, location bias or funding sources.

3.1.7 Data Synthesis

Due to the different data reporting of the outcomes measured in the included studies, effect sizes (Hedges'g) were calculated as the standardized mean difference (SMD) with mean ± SD and 95% confidence using Review Manager Software (RevMan 5.3; Cochrane Collaboration, Oxford, UK). Data were analysed using the ACLR limb compared with the dominant limb of the control group when limbs were not matched. The Cohen scale was used to interpret pooled SMD, where 0.2 represents a small effect, 0.5 a moderate effect, and 0.8 a large effect. Heterogeneity between studies was evaluated through I^2 statistics, the Cochrane Chi square (χ^2), and the between-study variance using the tau-square (τ^2) at the 95% CI. The categorization to rate the level of heterogeneity was the following: I^2 = 0%, no heterogeneity; I^2 = 1% to 25%, low heterogeneity, not important; I^2 = 26% to 50%, moderate heterogeneity; I^2 = 51% to 75%, high heterogeneity, substantial; I^2 = 76% to 100%, considerable heterogeneity (Higgins et al. , 2003). All studies containing variables eligible for meta-analysis were ordered in forest plots based on effect size. Subgroup analyses on graft types were conducted, where applicable (Schriger et al. , 2010). Levels of evidence (i.e. "strong", "moderate", "limited", "very limited" or "no evidence") were based on guidelines reported by van Tulder et al (van Tulder et al. , 2003) and previous reviews with similar included study types (Hart et al. , 2016, Kotsifaki, Korakakis, 2019), accounting for study quality and statistical homogeneity of the included studies in the data sets. Results are qualitatively and quantitatively synthesized and presented in three subgroups: 1) Strength; 2) Rate of force development and power; and 3) Reactive strength.

3.2 Results

3.2.1 Study Selection/Search Results

The electronic search initially identified 2023 articles from the databases (3156 before duplicates were removed); 1808 were excluded after reviewing the titles and abstracts. The full-text versions of the remaining 215 studies were obtained, of which 202 were subsequently excluded. 13 studies fulfilled the eligibility criteria and were included in this systematic review and meta-analysis. One study meeting the inclusion criteria was published after the initial electronic search (Read et al. , 2020b) and was subsequently included (figure 3.1). 12 of the included studies assessed strength, 2 measured single joint power contribution, 1 analysed RFD, and none evaluated reactive strength.

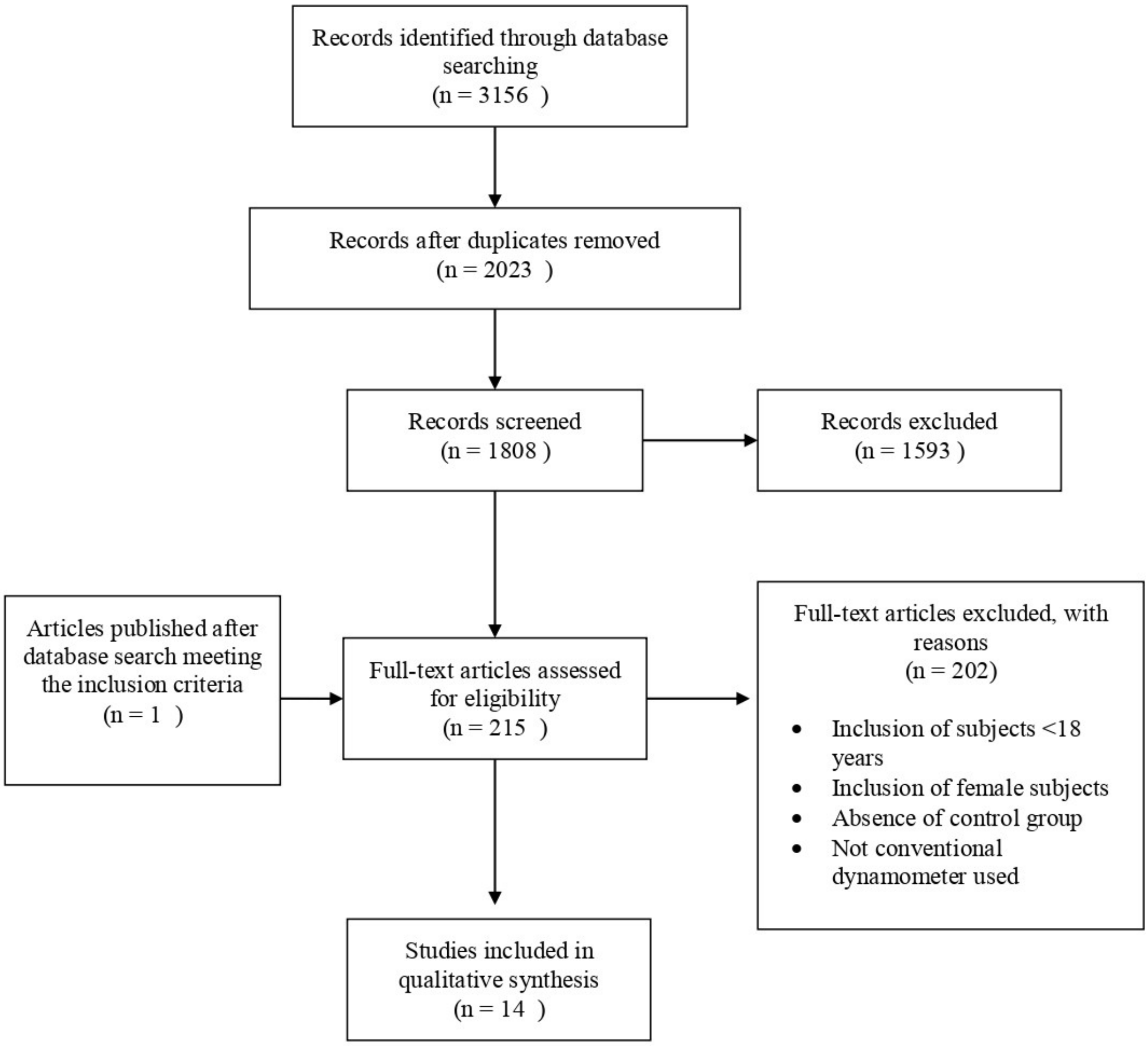

Figure 3.1 - Flow diagram

3.2.2 Study characteristics

Participants and study characteristics are summarized in Table 3.1. All studies included were controlled cohort trials. Eight studies analysed strength of knee extensor and flexors using isokinetic dynamometry (Almeida et al. , 2018, Baltaci et al. , 2012, Królikowska et al. , 2019, Miles and King, 2019, Mohammadi et al. , 2013, O'Malley, Richter, 2018, Welling et al. , 2019, Xergia et al. , 2013). Two studies assessed knee extensor and flexor strength using a stabilised dynamometer (Holsgaard-Larsen et al. , 2014, Norouzi et al. , 2019). One study investigated hip flexion strength with an isokinetic dynamometry (Mouzopoulos et al. , 2015) and another measured hamstring strength with a custom made device employing uniaxial load cells

(Timmins et al. , 2016) One study measured single joint power during a CMJ (Castanharo et al. , 2011) and the remaining study also assessed power and RFD in a CMJ (Read, Michael Auliffe, 2020b).

3.2.3 Level of evidence, study quality, and risk of bias within studies

The OCEBM level, PEDro and modified Downs and Black scores for each study can be found in Table 3.2 and 3.3. All 14 studies (100%) were classified as level 3b (cohort controlled trials). The risk of bias score was 6 (PEDro scale) for all studies (100%). The study quality was high (≥12) in 13 of the included articles, with the remaining study deemed as moderate (i.e., 11). There were no disagreements between the authors on the ratings.

Table 3.1 Summary of the included studies

AUTHOR(S), YEAR AND POPULATION STUDIES	PARTICIPANTS AND AGE (years)	INTERVENTIONS	COMPARISONS	OUTCOMES	STUDY DESIGN
Xergia (2013) Active population	22 BPTB 28.8 ± 11.2	Isokinetic concentric knee extension and flexion strength (120°/s, 180°/s, and 300°/s)	Contralateral limb Control group	Compared to the control group, the ACLR group had greater isokinetic knee extension torque deficits at all speeds ($p \leq .001$)	Controlled cohort study
Mohammadi (2013) Athletes involved in competitive sports	42 = 21BPTB + 21STG 25 ± 3	Isokinetic concentric knee extension and flexion strength (60°/s and 180°/s)	Between ACLR groups Contralateral limb Control group	No difference between BPTB and STG for hamstrings peak torque ($p = 0.69$ for 60°/s and $p = 0.63$ for 180°/s) or the limb symmetry index for the single-hop ($p = 0.78$) or 6-m-hop ($p = 0.74$) tests. STG group had greater values for quadriceps peak torque (13% and 17% change, $p = 0.004$) compared to the BPTB group. The ACLR limbs of both groups had lower peak torques ($p = 0.01$) compared to matched controls	Controlled cohort study
Miles (2019)	44 = 22BPTB + 22STG BPTB 23.4 ± 4.4	Isokinetic concentric knee extension and flexion strength (60°/s)	Between ACLR groups Contralateral limb Control group	BPTB had a greater knee extensor strength AAI than STG ($P = 0.002$, ES = 1.17) and controls	Controlled cohort study

Multidirectional sports	STG 26.1 ± 4.4			($P < 0.001$, ES = 1.40). No difference was found between STG and controls in knee extensor strength AAI ($P = 0.18$)	
O'Malley (2018) Multidirectional sports	118 Patellar tendon 23.6 ± 5.8	Isokinetic concentric knee extension and flexion strength (60°/s)	Contralateral limb Control group	**Between-Limbs Differences**: ISO knee-extension peak torque (ES=–1.33), SLCMJ knee power contribution (ES = –0.37), and ISO knee-flexion peak torque (ES = –0.19). **Between-Groups Differences:** ISO knee-extension LSI (ES = –1.53), LSImodified (ES =1.28), ISO knee-extension peak torque (ES = –1.20), hip power contribution (ES = 0.61), SL CMJ knee power contribution (ES = –0.40), and ISO knee-flexion peak torque (ES = –0.36).	Controlled cohort study
Castanharo (2011) Recreational sports activities	12 STG 28 ± 8	Knee joint power in CMJ	Contralateral limb Control group	In the ACLR group the peak knee joint power on the operated side was 13% lower than on the non-operated side ($p = 0.02$)	Controlled cohort study

Norouzi (2019) Multidirectional sports (football players)	27 23.8 ± 3.3	Knee extensor strength (using a stabilised dynamometry)	Passed and failed RTS criteria groups Contralateral limb Control group	No significant difference between the 3 groups in terms of the quadriceps strength symmetry index ($p > 0.05$)	Controlled cohort study
Holsgaard-Larsen (2014) Active population	23 STG 27.2 ± 7.5	MVC knee extensors and flexors (using stabilized dynamometry)	Contralateral limb Control group	Asymmetry in hamstring MVC was greater ($p < 0.001$) for ACLR participants than controls (77.4% vs. 101.3%)	Controlled cohort study
Read (2020) Multidirectional sports (elite soccer players)	124= 69 (6-9 months) + 55 (>9 months) 6-9 months 23.7 ± 6.7 >9 months 24.0 ± 5.4	Eccentric deceleration RFD in CMJ	Between ACLR groups Contralateral limb Control group	Between-limb differences in eccentric deceleration RFD remained significantly greater in players >9 months after ACLR versus matched controls ($p<0.05$).	Controlled cohort study

Welling (2019) Multidirectional sports (amateur soccer players)	38 24.2±4.7	Isokinetic concentric knee extension and flexion strength (60°/s)	Contralateral limb Control group	Soccer players after ACLR had no significant differences in peak quadriceps and hamstring muscle strength in the injured leg at 7 months after ACLR compared to the dominant leg of the control group. Furthermore, 65.8% of soccer players after ACLR passed LSI >90% at 10 months for quadriceps muscle strength	Controlled cohort study
Królikowska (2019) Active people	Group 1= 77 STG Group 2= 66 STG	Isokinetic concentric knee extension and flexion strength (60°/s and 180°/s)	Between ACLR groups Contralateral limb Control group	The shift towards extension was noted when comparing the ACL-reconstructed limb to the uninvolved limb (Group I, $p \leq 0.001$; Group II, $p \leq 0.001$) and to Group III ($p \leq 0.001$), but it was not correlated with physiotherapy supervision duration ($r = -0.037$, $p = 0.662$). In ACLR patients, there was a moderate association of supervision duration and knee flexor LSI ($r = 0.587$, $p < 0.001$).	Controlled cohort study
Almeida (2018) Multidirectional sports (elite soccer players)	20 STG Median 21 (18-28)	Isokinetic concentric knee extension and flexion strength (60°/s)	Contralateral limb Control group	At 6 months post-surgery knee function questionnaires and quadriceps peak torque deficit improved after surgery but were significantly lower compared to controls.	Controlled cohort study

Mouzopoulos (2015) Weekend athletes	32 BPTB 36 STG 26.2±5.6	Isokinetic hip flexor contraction at an angular velocity of 120°/seconds and 60°/seconds in a concentric and eccentric mode were performed	Between ACLR groups Contralateral limb Control group	Hip flexion strength in ACL reconstructed patients either with patellar tendon or hamstrings grafts, one year after reconstruction is significantly decreased compared to healthy controls ($p<0.0001$). Patients reconstructed with patellar tendon have stronger hip flexors than those reconstructed with hamstrings graft ($p<0.0001$)	Controlled cohort study
Baltaci (2012) Not specified	15 29.6±5.9	Isokinetic concentric knee extension and flexion strength (60°/s and 180°/s)	Contralateral limb Control group	When the operated knees were compared to the healthy side, mean limb symmetry index was over 92% (with two cases at 88%). When the dominant leg was compared to the non-dominant leg in the control group, the mean limb symmetry index was over 95%.	Controlled cohort study
Timmins (2016) Multidirectional sports (elite soccer and AFL players)	15 ST 24.5±4.2	MVIC of knee flexor at 0°, and average peak force during the Nordic hamstring exercise	Contralateral limb Control group	Eccentric strength was lower in the ACLR limb when compared with the contralateral uninjured limb. Fascicle length, MVIC, and eccentric strength were not different between the left and right limb in the control group	Controlled cohort study

Table 3.2 PEDro score of each study

PEDro Scale	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11	Total Score
Xergia SA (2013)	√	X	X	√	X	X	X	√	√	√	√	6
Mohammadi F (2013)	√	X	X	√	X	X	X	√	√	√	√	6
Miles JJ (2019)	√	X	X	√	X	X	X	√	√	√	√	6
O'Malley E (2018)	√	X	X	√	X	X	X	√	√	√	√	6
Castanharo R (2011)	√	X	X	√	X	X	X	√	√	√	√	6
Norouzi S (2019)	√	X	X	√	X	X	X	√	√	√	√	6
Holsgaard-Larsen A (2014)	√	X	X	√	X	X	X	√	√	√	√	6
Read P (2020)	√	X	X	√	X	X	X	√	√	√	√	6
Welling (2019)	√	X	X	√	X	X	X	√	√	√	√	6
Królikowska (2019)	√	X	X	√	X	X	X	√	√	√	√	6
Almeida (2018)	√	X	X	√	X	X	X	√	√	√	√	6
Mouzopoulos (2015)	√	X	X	√	X	X	X	√	√	√	√	6
Baltaci (2012)	√	X	X	√	X	X	X	√	√	√	√	6
Timmins (2016)	√	X	X	√	X	X	X	√	√	√	√	6

Table 3.3 OCEBM level and Modified Downs and Black scores of each study

Modified Downs and Black Scores	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11	Item 12	Item 13	Item 14	Item 15	Total Score	**OCEBM level (Lv)**
Xergia SA (2013)	1	1	1	1	1	1	1	0	1	1	1	2	0	1	1	14	Lv3b
Mohammadi F (2013)	1	1	1	1	1	1	1	0	1	1	1	2	0	1	1	14	Lv 3b
Miles JJ (2019)	1	1	1	1	1	1	1	0	1	1	1	2	0	1	1	14	Lv 3b
O'Malley E (2018)	1	1	1	1	1	1	1	0	1	1	1	2	0	1	1	14	Lv 3b
Castanharo R (2011)	1	1	1	1	1	1	1	0	1	1	1	2	0	0	1	13	Lv 3b
Norouzi S (2019)	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	12	Lv 3b
Holsgaard-Larsen A (2014)	1	1	1	1	1	1	1	0	1	1	1	2	0	1	1	14	Lv 3b
Read P (2020)	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	12	Lv 3b
Welling (2019)	1	1	1	1	1	1	1	0	1	1	1	1	0	1	1	13	Lv 3b
Królikowska (2019)	1	1	1	1	1	1	1	0	1	1	1	2	0	1	1	14	Lv 3b
Almeida (2018)	1	1	1	1	1	1	1	0	1	1	1	2	0	1	1	14	Lv 3b
Mouzopoulos (2015)	1	1	1	1	1	1	1	0	1	1	1	2	0	0	0	12	Lv 3b
Baltaci (2012)	1	1	1	1	1	1	1	0	1	1	1	1	0	0	0	11	Lv 3b
Timmins (2016)	1	1	1	1	1	1	1	0	1	1	1	2	0	1	1	14	Lv 3b

3.2.4 Risk of bias across studies

Of the 14 studies included, 7 reported to have received some funding in support to their research. All authors reported no conflicts of interest. There was no selective data reporting in all studies examined. 3 articles were published in open access journals with chargeable publication fees.

3.2.5 Results of individual studies

3.2.5.1 Strength

The total number of ACLR participants included in this systematic review was 701. Xergia et al. (Xergia, Pappas, 2013) examined strength in participants (n=22) at approximately 7 months post-ACLR (bone-patellar tendon-bone graft (BPTB)). They found reduced strength in the ACLR limb compared to controls (n=22), and inter-limb asymmetries in the ACLR group. Norouzi et al. (Norouzi, Esfandiarpour, 2019) analysed strength in 3 different groups: 1) healthy controls (n=15); 2) ACLR participants who passed (n=14); and 3) failed RTS criteria (n=13). They showed no significant difference between ACLR and healthy participants in strength at an average of 7.5 months following surgery. Holsgaard-Larsen et al. (Holsgaard-Larsen, Jensen, 2014) measured strength in ACLR (n=23) and healthy participants (n=25 with matched MET score) at approximately 2 years post ACLR. They found greater inter-limb strength asymmetries in ACLR vs. healthy participants. Mohammadi et al. (Mohammadi, Salavati, 2013) assessed strength in male soccer players (n=21 BPTB and semitendinosus and gracilis tendon (n=21 STG graft) and matched controls (n=21). The results revealed strength deficits between the ACLR limb and healthy controls at 8 months post-surgery. Miles et al. (Miles and King, 2019) (n=44) assessed strength in ACLR (BPTB and STG groups) and healthy participants (n=22) during late phase rehabilitation, reporting between group differences and greater inter-limb asymmetries only in ACLR participants. Similarly, O'Malley et al. (O'Malley, Richter, 2018) evaluated strength in individuals at least 6 months after ACLR (n=118 Patellar Tendon (PT)) and healthy participants (n=44). They also showed between groups differences and greater inter-limb asymmetries only in ACLR participants. Welling et al. (Welling, Benjaminse, 2019) measured strength in 38 amateur male soccer players at two different time-points (7 and 10 months) post ACLR (14 BPTB 24 STG) and healthy participants (n=30). They found no differences between groups in peak torque at 7 and

10 months, with the exception of the hamstrings which was greater in the ACLR group at 10 months.

Krolikowska et al. (Królikowska, Reichert, 2019) examined strength in 2 groups of active males (total n=143 STG) (randomized based on the completion or not of ≥ 6 months postoperative physiotherapy supervision). Assessment took place at approximately 7 months post ACLR in comparison with matched controls (n=98). They observed reduced strength and significant inter-limb asymmetries in the ACLR participants compared to matched controls. Almeida et al. (Almeida, Santos Silva, 2018) showed significant differences in strength and inter-limb strength asymmetries in professional soccer players at 6 months post ACLR (n=20 STG) compared to healthy players (n=20). Mouzopoulos et al. (Mouzopoulos, Siebold, 2015) found strength differences between amateur male athletes 1 year post ACLR (n=68, 32 BPTB 36 STG) and healthy controls (n=68). Baltaci et al. (Baltaci, Yilmaz, 2012) revealed no significant difference in strength between limbs and groups in male adults 20 months post ACLR (n=15) and matched controls (n=15). Timmins et al. (Timmins, Bourne, 2016) evaluated strength in 15 (ST) elite athletes who had returned to pre-injury levels of competition and training following ACLR (median time since surgery= 3.5 years), indicating greater strength deficits and greater inter-limb asymmetries compared to matched controls (n=52).

3.2.5.2 RFD and power

Castanharo et al. (Castanharo, da Luz, 2011) measured single joint power in a CMJ in a ACLR (n=12) and a non-injured control group (n=17). At more than 2 years post-surgery, they found reduced knee joint power on the ACLR side than the contralateral limb, but no differences in jump height between groups. Similarly, O’Malley et al. (O'Malley, Richter, 2018) reported significant between limbs and group differences in knee and hip power contribution during a single leg CMJ in multidirectional sport athletes > 6 months (n=118) following ACLR compared to healthy controls (n=44). Read et al. (Read, Michael Auliffe, 2020b) measured RFD and peak power during a bilateral CMJ in ACLR (n=124) participants (at 6-9 and >9 months post-surgery) and matched controls (n=204). The results showed significant between groups and inter-limb differences in peak power and eccentric deceleration RFD between the ACLR participants and healthy controls.

3.2.6 Synthesis of results

Due to the different assessment modes, only 5 of the 14 studies were deemed eligible for inclusion in a meta-analysis (262 participants) (Almeida, Santos Silva, 2018, Miles and King, 2019, Mohammadi, Salavati, 2013, O'Malley, Richter, 2018, Welling, Benjaminse, 2019). These studies measured peak knee extension and flexion torque with an isokinetic dynamometer at 60°/s in participants involved in multidirectional sports. Separate analysis was also performed to examine differences based on different graft types (BPTB/PT and STG). If studies contained measures taken at different time points, only the data measured at the first time point beyond the 6 months post-surgical period were used in the meta-analysis. Comparisons between the ACLR limb and the dominant limb of the healthy group were quantitatively synthesised. The uninvolved limb was not considered as a suitable reference limb due to the bilateral strength reductions observed in the post-surgical period (Wellsandt et al. , 2017a). Knee extension and flexion strength pooled results are presented in Figure 3.2,3.3,3.4 and 3.5.

3.2.6.1 Peak knee extension strength

Pooled data showed moderate evidence indicating a large negative effect (*g*= -0.96, 95% CI [-1.30,-0.62]; I^2=51%) of ACLR on involved limb peak knee extension torque compared to the dominant limb of the healthy controls at more than 6 months post-surgery. Subgroup analysis revealed no significant difference between groups (BPTB/PT vs STG, *p*= 0.19), showing strong evidence of a large effect of ACLR on knee extension peak torque in BPTB/PT (*g*= -1.29, 95% CI [-1.60,-0.97]; I^2=0%) reconstructed knees compared to the dominant limb of healthy controls. Moderate evidence of a large effect was shown in STG (*g*= -0.81, 95% CI [-1.47,-0.15]; I^2=59%) reconstructed knees compared to the dominant limb of healthy controls.

3.2.6.2 Peak knee flexion strength

Pooled data showed moderate evidence indicating a small negative effect (*g*= -0.45, 95% CI [-0.67,-0.23]; I^2=5%) of ACLR on peak knee flexion torque on the involved limb compared to the dominant limb of the healthy controls > 6 months post-surgery. Subgroups analysis revealed no significant difference between groups (BPTB/PT vs STG, *p*= 0.10), showing strong evidence of a moderate effect of ACLR on knee flexion peak torque in BPTB/PT (*g*= -0.37, 95% CI [-0.66,-0.08]; I^2=0%), and strong evidence of a large effect in STG (*g*= -0.80, 95% CI [-1.22,-0.38]; I^2=0%) reconstructed knees compared to the dominant limb of healthy controls.

Study or Subgroup	ACLR Mean	ACLR SD	ACLR Total	Controls Mean	Controls SD	Controls Total	Weight	Std. Mean Difference IV, Random, 95% CI
Almeida STG 2018	291.3	45.5	20	358	44.2	20	13.0%	-1.46 [-2.16, -0.75]
O'Malley PT 2018	200.2	44.9	118	260.8	37.2	44	21.5%	-1.40 [-1.78, -1.02]
Mohammadi BPTB 2013	218.28	28.64	21	253.35	28.15	11	11.3%	-1.20 [-1.99, -0.41]
Miles BPTB 2019	219.95	68.48	22	272.53	28.4	11	11.9%	-0.88 [-1.63, -0.12]
Welling 2019	290	50	38	320	30	30	18.1%	-0.70 [-1.19, -0.21]
Miles STG 2019	251.95	46.1	22	272.53	28.4	11	12.4%	-0.49 [-1.22, 0.25]
Mohammadi STG 2013	243.57	25.71	21	253.35	28.15	10	11.9%	-0.36 [-1.12, 0.40]
Total (95% CI)			**262**			**137**	**100.0%**	**-0.96 [-1.30, -0.62]**

Heterogeneity: Tau² = 0.10; Chi² = 12.30, df = 6 (P = 0.06); I² = 51%
Test for overall effect: Z = 5.53 (P < 0.00001)

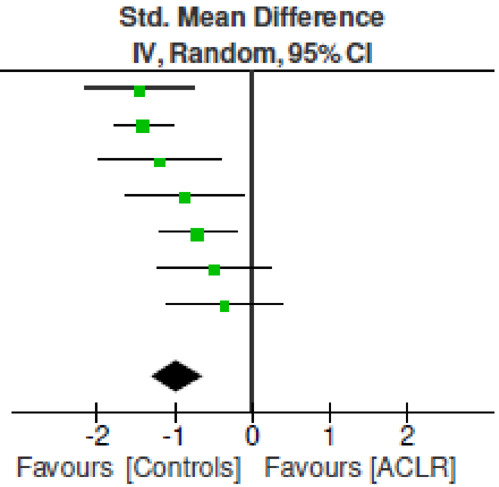

Figure 3.2 Forest plot for peak knee extension strength comparing the ACL reconstructed limb with the dominant limb of healthy controls. Studies are ordered according to effect size. (ACLR) anterior cruciate ligament reconstruction; (STG) semitendinosus and gracilis tendon graft; (BPTB) bone-patellar tendon-bone graft; (PT) patellar tendon graft.

Study or Subgroup	ACLR Mean	ACLR SD	ACLR Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Miles STG 2019	144.75	23.96	22	172.43	27.9	11	8.0%	-1.07 [-1.84, -0.29]
Almeida STG 2018	166.1	30.9	20	190.5	18.5	20	11.0%	-0.94 [-1.60, -0.28]
Mohammadi BPTB 2013	130.96	17.73	21	138.07	17.42	11	8.8%	-0.39 [-1.13, 0.34]
Miles BPTB 2019	159.38	36.96	22	172.43	27.9	11	8.9%	-0.37 [-1.10, 0.36]
O'Malley PT 2018	145.7	28.5	118	155.9	24.3	44	35.2%	-0.37 [-0.72, -0.02]
Mohammadi STG 2013	131.25	18.94	21	138.07	17.42	10	8.3%	-0.36 [-1.12, 0.40]
Welling 2019	182.02	37.85	38	187.48	29.02	30	19.8%	-0.16 [-0.64, 0.32]
Total (95% CI)			**262**			**137**	**100.0%**	**-0.45 [-0.67, -0.23]**

Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 6.32$, $df = 6$ ($P = 0.39$); $I^2 = 5\%$

Test for overall effect: $Z = 3.95$ ($P < 0.0001$)

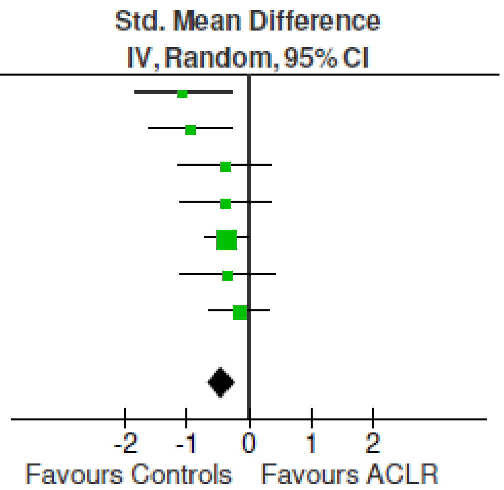

Figure 3.3 Forest plot for peak knee flexion strength comparing the ACL reconstructed limb with the dominant limb of healthy controls. Studies are ordered according to effect size. (ACLR) anterior cruciate ligament reconstruction; (STG) semitendinosus and gracilis tendon graft; (BPTB) bone-patellar tendon-bone graft; (PT) patellar tendon graft.

Study or Subgroup	ACLR Mean	ACLR SD	ACLR Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.1.1 STG graft								
Almeida STG 2018	291.3	45.5	20	358	44.2	20	15.9%	-1.46 [-2.16, -0.75]
Miles STG 2019	251.95	46.1	22	272.53	28.4	11	15.2%	-0.49 [-1.22, 0.25]
Mohammadi STG 2013	243.57	25.71	21	253.35	28.15	10	14.7%	-0.36 [-1.12, 0.40]
Subtotal (95% CI)			**63**			**41**	**45.8%**	**-0.78 [-1.47, -0.09]**
Heterogeneity: $Tau^2 = 0.23$; $Chi^2 = 5.33$, df = 2 (P = 0.07); $I^2 = 62\%$								
Test for overall effect: Z = 2.21 (P = 0.03)								
1.1.2 BPTB graft								
O'Malley PT 2018	200.2	44.9	118	260.8	37.2	44	25.6%	-1.40 [-1.78, -1.02]
Mohammadi BPTB 2013	218.28	28	21	253.35	28.15	11	13.9%	-1.22 [-2.01, -0.42]
Miles BPTB 2019	219.95	68.48	22	272.53	28.4	11	14.7%	-0.88 [-1.63, -0.12]
Subtotal (95% CI)			**161**			**66**	**54.2%**	**-1.29 [-1.60, -0.97]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 1.53$, df = 2 (P = 0.47); $I^2 = 0\%$								
Test for overall effect: Z = 8.08 (P < 0.00001)								
Total (95% CI)			**224**			**107**	**100.0%**	**-1.02 [-1.40, -0.63]**
Heterogeneity: $Tau^2 = 0.11$; $Chi^2 = 10.20$, df = 5 (P = 0.07); $I^2 = 51\%$								
Test for overall effect: Z = 5.16 (P < 0.00001)								
Test for subgroup differences: $Chi^2 = 1.72$, df = 1 (P = 0.19), $I^2 = 41.9\%$								

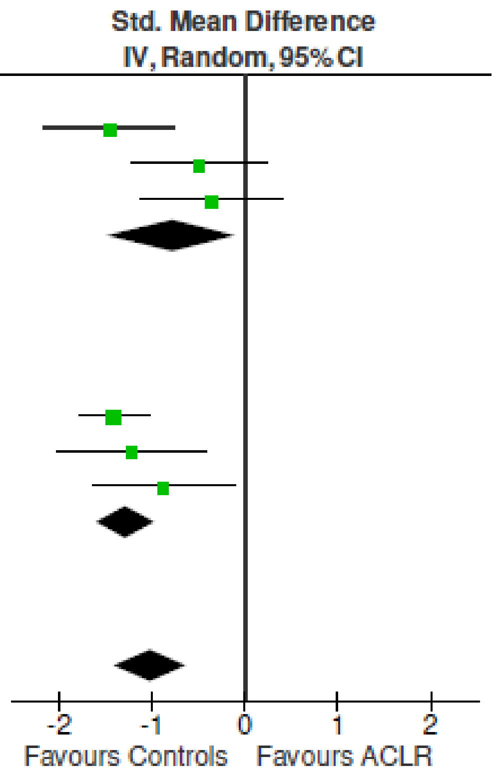

Figure 3.4 Forest plot for peak knee extension strength comparing the ACL reconstructed limb (STG and BPTB/PT) with the dominant limb of healthy controls. Studies are ordered according to effect size. (ACLR) anterior cruciate ligament reconstruction; (STG) semitendinosus and gracilis tendon graft; (BPTB) bone-patellar tendon-bone graft; (PT) patellar tendon graft.

	ACLR			Control				Std. Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
1.2.1 STG graft								
Miles STG 2019	144.75	23.96	22	172.43	27.9	11	9.4%	-1.07 [-1.84, -0.29]
Almeida STG 2018	166.1	30.9	20	190.5	18.5	20	13.1%	-0.94 [-1.60, -0.28]
Mohammadi STG 2013	131.25	18.94	21	138.07	17.42	10	9.8%	-0.36 [-1.12, 0.40]
Subtotal (95% CI)			**63**			**41**	**32.4%**	**-0.80 [-1.22, -0.38]**
Heterogeneity: Tau² = 0.00; Chi² = 1.93, df = 2 (P = 0.38); I² = 0%								
Test for overall effect: Z = 3.75 (P = 0.0002)								
1.2.2 BPTB graft								
Mohammadi BPTB 2013	130.96	17.73	21	138.07	17.42	11	10.4%	-0.39 [-1.13, 0.34]
Miles BPTB 2019	159.38	36.96	22	172.43	27.9	11	10.6%	-0.37 [-1.10, 0.36]
O'Malley PT 2018	145.7	28.5	118	155.9	24.3	44	46.6%	-0.37 [-0.72, -0.02]
Subtotal (95% CI)			**161**			**66**	**67.6%**	**-0.37 [-0.66, -0.08]**
Heterogeneity: Tau² = 0.00; Chi² = 0.00, df = 2 (P = 1.00); I² = 0%								
Test for overall effect: Z = 2.53 (P = 0.01)								
Total (95% CI)			**224**			**107**	**100.0%**	**-0.51 [-0.75, -0.27]**
Heterogeneity: Tau² = 0.00; Chi² = 4.64, df = 5 (P = 0.46); I² = 0%								
Test for overall effect: Z = 4.22 (P < 0.0001)								
Test for subgroup differences: Chi² = 2.71, df = 1 (P = 0.10), I² = 63.1%								

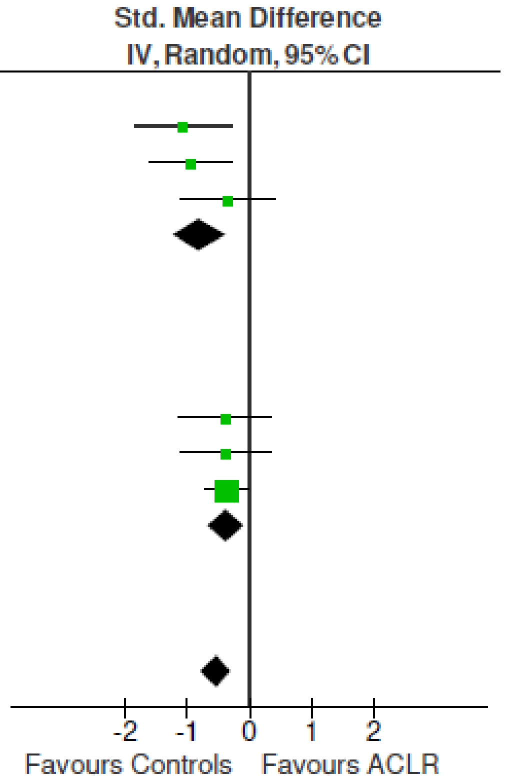

Figure 3.5 Forest plot for peak knee flexion strength comparing the ACL reconstructed limb (STG and BPTB/PT) with the dominant limb of healthy controls. Studies are ordered according to effect size. (ACLR) anterior cruciate ligament reconstruction; (STG) semitendinosus and gracilis tendon graft; (BPTB) bone-patellar tendon-bone graft; (PT) patellar tendon graft.

3.3 Discussion

The aim of this review was to synthesize and critically evaluate the available literature pertaining to athletic performance capacities in physically active adult males who were in the later stages of rehabilitation (> 6 months) post ACLR compared to healthy, non-injured controls. Our particular focus was on strength, RFD, power, and reactive strength, to more clearly elucidate the magnitude of performance deficits compared to the healthy matched controls. The main findings revealed significant deficits and greater between limb asymmetries in knee extensor and flexor strength. Also, lower peak knee joint power at the knee in the ACLR limb during jumping tasks appears compensated by a higher proportion of power generated at the hip. Preliminary evidence also indicated that reductions in eccentric deceleration RFD on the involved limb are present in male adults at more than 6 months following ACLR, compared to matched controls.

3.3.1 Effect of ACLR on maximal strength measured during isokinetic dynamometry

The magnitude of residual deficits in knee extension strength following ACLR showed moderate to large effect sizes in injured male multidirectional field sport athletes who were > 6 months post-surgery in comparison to healthy individuals (Almeida, Santos Silva, 2018, Miles and King, 2019, Mohammadi, Salavati, 2013, O'Malley, Richter, 2018, Welling, Benjaminse, 2019). Compared to the dominant limb of matched controls, the ACLR limb displayed large deficits in knee extension peak torque (g= -0.96, 95% CI [-1.30,-0.62]) and small deficits in knee flexion peak torque (g= -0.45, 95% CI [-0.67,-0.23]). Deficits in knee extension peak torque were further pronounced in BPTB/PT grafts (g= -1.29, 95% CI [-1.60,-0.97]), whereas deficits in knee flexion peak torque were more evident in STG grafts (g= -0.80, 95% CI [-1.22,-0.38]). This may have significant implications for re-injury risk considering that quadriceps strength deficits prior to return to multidirectional sport is a significant predictor of knee re-injury (Grindem, Snyder-Mackler, 2016, Wellsandt, Failla, 2017a). Furthermore, knee extensor strength deficits have been associated with lower levels of self-reported outcomes (Perraton et al. , 2017, Pietrosimone et al. , 2016), increased risk of osteoarthritis (Sinding et al. , 2020), impaired functional performance (Birchmeier, Lisee, 2019), and quality of life (Filbay et al. , 2014). Furthermore, linear regression models have shown small to moderate correlation values between peak knee extension torque, kinetic and kinematic variables in individuals following ACLR (Birchmeier, Lisee, 2019, Miles and King, 2019, O'Malley, Richter, 2018); thus, suggesting a significant interaction among fundamental physical capacities such as strength and more complex athletic tasks.

Level of sports participation may be an important factor to consider. One study (Almeida, Santos Silva, 2018) analysed professional soccer players in Brazilian football teams at 6 months post ACLR and revealed large differences in knee extension peak torque in the reconstructed knee (291.3 ± 45.5 Nm/Kg) compared to the dominant limb of healthy professional soccer players (358 ± 44.2 Nm/Kg). Conversely, in Dutch amateur soccer players who were 7 months post-surgery (Welling, Benjaminse, 2019), no significant differences were present. As the healthy control group consisting of professional players [56] achieved higher peak torque values than amateur non-injured controls [54], this reinforces the need to consider absolute and relative torque values and not just limb symmetry. In addition, strength values in the later stages of rehabilitation, where possible, should compare performance to normative values representative of the athletes level of competition to account for the unique characteristics and functional demands of the studied population.

Only one study included in our review included a progressive strength training intervention during rehabilitation in athletes post ACLR, comparing maximal strength to healthy controls at 4, 7 and 10 months after surgery (Welling, Benjaminse, 2019). Results showed that the documented program (mean frequency 2.6 sessions per week), as outlined by the American College of Sports Medicine (Garber et al. , 2011), was effective not only in attenuating strength deficits at 7 months (g=-0.19, 95%CI [-0.67, 0.29]), but also to reach superior values (>3.0 Nm/kg) than the dominant limb of healthy controls and LSI of more than 90% by 10 months. These findings indicate that observed residual strength deficits (Almeida, Santos Silva, 2018, Holsgaard-Larsen, Jensen, 2014, Królikowska, Reichert, 2019, Miles and King, 2019, Mohammadi, Salavati, 2013, Mouzopoulos, Siebold, 2015, O'Malley, Richter, 2018, Timmins, Bourne, 2016, Welling, Benjaminse, 2019, Xergia, Pappas, 2013) are trainable and levels of performance comparable to healthy controls are possible during rehabilitation following ACLR. Thus, sports and healthcare professionals should be encouraged to adopt targeted rehabilitation strategies focusing on maximal strength, that include specific exercise selection, dosage and progressions. Briefly, current evidence indicates single-joint (e.g. leg extension/curl) and multi-joint exercises (e.g. split squat, front/back squat, deadlift) involving a load (or intensity) of 80-100% of the participant’s one RM, utilizing approximately 1-6 repetitions, across 3-5 sets, with rest periods of 3-5 minutes, and a frequency of 2-3 times per week (2009, Morton et al. , 2019, Suchomel, Nimphius, 2018). For detailed information regarding practical applications to return athletes to high performance we recommend recently published articles (Buckthorpe, 2019, Buckthorpe and Della Villa, 2019, Lorenz and Reiman, 2011, Maestroni, Read, 2020, Welling, Benjaminse, 2019).

Our findings also show that graft type needs to be taken into consideration when assessing maximal strength and subsequently designing rehabilitations programs. Independent from graft type, knee extensor strength in multidirectional athletes > 6 months following ACLR appear significantly compromised (g= -0.96, 95% CI [-1.30,-0.62]). Knee flexor strength also targeted interventions due to residual deficits in hamstring strength (g= -0.45, 95% CI [-0.67,-0.23]), especially in athletes whose elected surgery was a STG (g= -0.80, 95% CI [-1.22,-0.38]). Differences between graft types were also observed in studies analysing knee extension and flexion strength in recreational athletes at isokinetic velocities different than 60°/s (Królikowska, Reichert, 2019, Xergia, Pappas, 2013). More pronounced knee extension strength deficits were found in BPTB grafts (Xergia, Pappas, 2013), whereas knee flexion strength deficits were more evident in STG grafts (Królikowska, Reichert, 2019). In addition, one study (Mouzopoulos, Siebold, 2015) showed significantly greater hip flexion strength (measured concentrically and eccentrically at 60°/s and 120°/s) in amateur male athletes with a BPTB graft (n=32) than in the STG group (n=36) at 1-year post ACLR (p<0.0001). Both groups displayed inferior values when compared to matched controls.

3.3.2 Assessment modes to determine maximal strength

The majority of studies used an isokinetic dynamometer at a variety of test speeds (60°/s,120°/s,180°/s and 300°/s) for both the quadriceps and hamstring muscles (Almeida, Santos Silva, 2018, Baltaci, Yilmaz, 2012, Królikowska, Reichert, 2019, Miles and King, 2019, Mohammadi, Salavati, 2013, O'Malley, Richter, 2018, Welling, Benjaminse, 2019, Xergia, Pappas, 2013). Other testing modes included isometric MVIC on a dynamometer (Holsgaard-Larsen, Jensen, 2014, Norouzi, Esfandiarpour, 2019, Timmins, Bourne, 2016), or uniaxial load cells (Timmins, Bourne, 2016) Surprisingly, none of the eligible and included studies evaluated multi-joint strength levels (e.g. back squats, isometric mid-thigh pull). Although single-joint strength assessment is required and provides an indication of specific deficits in muscles directly associated with the injured site following ACLR, research has shown that multi-joint strength capacities display a heightened transfer to athletic performance (Suchomel, Nimphius, 2018). Specifically, moderate to high correlations between multi-joint strength levels and jumping, sprinting and COD performance were reported in a recent systematic review (Suchomel et al. , 2016). Therefore, future research is warranted to examine 'global system' strength in athletes following ACLR to determine their level of readiness to re-perform using sport relevant capacity tests.

The two studies that measured quadriceps MVIC (Holsgaard-Larsen, Jensen, 2014, Norouzi, Esfandiarpour, 2019) with a stabilized dynamometry (in sitting at 90° knee flexion) did not detect any knee extension MVIC deficit compared to the contralateral limb. Instead, conflicting results were found in knee flexion MVIC. One study (Holsgaard-Larsen, Jensen, 2014) showed 22% inter-limb asymmetry in hamstring MVIC (measured in 90° knee flexion), whereas no differences were observed when hamstring MVIC was tested at 0° knee flexion (Timmins, Bourne, 2016). It appears that differences in quadriceps strength were more apparent in studies using isokinetic dynamometry (Almeida, Santos Silva, 2018, Miles and King, 2019, Mohammadi, Salavati, 2013, O'Malley, Richter, 2018, Welling, Benjaminse, 2019), which may be more sensitive in detecting strength deficits throughout the range of motion analysed, compared to a stabilized dynamometry at a specific joint-angle only. Also, these results indicate that measuring hamstrings strength at a specific joint angle may not be sufficient to detect deficits. Although knee positions near full extension are often frequently reported as part of the ACL injury mechanism (Walden et al. , 2015), it is also important to note that smaller knee flexion angles (i.e. < 30°) expose the ACL to high strain magnitudes (Markolf et al. , 1995, Petersen and Zantop, 2007, Yasuda et al. , 2008), which may preclude assessment in these ranges during the earlier stages of rehabilitation. In most studies using isokinetic dynamometry, it is unclear at which angle peak torque occurred. Therefore, information about muscle performance during specific ranges of motion or shifts in peak torque angles occurring following ACLR are limited, with existing studies reporting contrasting results (Cinar-Medeni et al. , 2019, Makihara et al. , 2006, Ohkoshi et al. , 1998). Among the studies included in this review, only Krolikowska et al. (Królikowska, Reichert, 2019) reported a shift of ACLR limb knee flexor muscles peak torque angle at 180˚/s towards extension in participants with shorter supervised post-surgical rehabilitation, compared to the other two groups.

3.3.3 Effect of ACLR on maximal strength – summary of findings

Taken together, the synthesized data from our review suggests that: 1) isokinetic dynamometry is more sensitive in detecting force production deficits than MVIC assessment; 2) subjects receiving a BPTB autograft display greater deficits in quadriceps strength and should be more closely monitored in their knee extensor strength capacity over the course of rehabilitation and prior to RTS; 3) subjects receiving STG autograft show deficits in hamstring strength although this is not consistent across all studies which imply particular attention during rehabilitation; 4) subjects receiving a BPTB autograft might be slower in achieving key rehabilitation milestones such as 90% LSI; 5) physiotherapy programs with specific emphasis on strength are capable of achieving the targeted strength values comparable to those of healthy matched controls; 6) in addition to LSI and absolute peak forces, normative values appear of utmost importance to assess rehabilitation status to remove the confounding factor of using the contralateral limb as the only reference value which may overestimate knee function.

3.3.4 Effect of ACLR on rate of force development and power

Only one study (Read, Michael Auliffe, 2020b) meeting our inclusion criteria reported RFD in physically active male adults following ACLR compared to controls at more than 6 months post ACLR. Read et al. (Read, Michael Auliffe, 2020b) showed that eccentric deceleration RFD on the involved limb was significantly lower in athletes > 6 months post ACLR vs. matched controls and they also displayed a greater eccentric deceleration RFD asymmetry index. Interestingly, no meaningful between group differences were observed in eccentric mean force. Eccentric deceleration RFD provides an indication of the rate of force rise as the athletes decelerate their mass in the final phase of the descent. Eccentric mean force examines the entire lowering phase and these data suggest that rate-related variables may be more sensitive to identify between-limb deficits after injury but this requires further investigation.

Castanharo et al. (Castanharo, da Luz, 2011) assessed single joint power contributions (i.e. physical capacity containing both force and velocity) in the CMJ, comparing an ACLR group (adult males with STG graft ≥ 2 years post-surgery) to a control group. They found no significant differences in jump height between groups, but peak knee joint power on the ACLR limb was 13% lower than the contralateral side. O'Malley et al. (O'Malley, Richter, 2018) also reported significant inter-limb asymmetries in hip power contribution (d=0.75), knee power contribution (d= -0.37) and single leg CMJ peak power (d= -0.47, β=0.99). Similar differences in peak power $LSI_{modified}$ (d = –0.61), hip (d = 0.61), and knee power contribution (d = –0.40) were also found between the ACLR limb and the dominant limb of the control group. Collectively, these studies indicated that in the ACLR limb, a higher proportion of power is generated at the hip to compensate lower peak knee joint power when generating propulsive forces in tasks such as unilateral jumping. No values regarding the epoch taken to generate force were reported. Therefore, speculation of differences in RFD in the different phases of the CMJ cannot be made. This impeded accurate data extraction regarding RFD values in these studies.

Although there was a paucity of data to examine the effect of ACLR on RFD, the ability of key musculature such as the quadriceps to generate force rapidly in ACLR cohorts is important to optimise lower extremity loading characteristics in hopping and jumping (Birchmeier, Lisee, 2019, Pua, Mentiplay, 2017). Therefore, knee extensor RFD/RTD has been suggested as a useful component to include in RTS decision making (Angelozzi, Madama, 2012, Hsieh, Indelicato, 2015). Furthermore, Angelozzi et al. (Angelozzi, Madama, 2012) showed that although peak force differences between-limbs had normalised 6 months post ACLR, residual deficits in RFD during and isometric leg press were identified. However, these authors (Angelozzi, Madama, 2012) also showed that targeted interventions are successful in restoring these capacities to their pre-injury levels. Further research is warranted to investigate if deficits in eccentric deceleration RFD are trainable and if deficits in this physical capacity are associated with the secondary injuries following ACLR.

3.3.5 Effect of ACLR on reactive strength

We did not find any studies meeting our inclusion criteria that measured reactive strength in physically active male adults who were more than 6 months following ACLR in comparison to matched controls. King et al. (King, Richter, 2018b) examined RSI in an ACLR male adult population involved in multidirectional sports approximately at 9 months post-surgery (n =156, mean age 24.8 ± 4.8) although this study did not include a control group. Reductions in RSI were observed in the ACLR limb compared to the contralateral (21% between-limb deficit; *d* = −0.73.). Previously, Flanagan et al. (Flanagan et al. , 2008) evaluated RSI in ten participants (8 men, 2 women at a mean time from ACLR of 27.0 ± 14.5 months) using a jump sledge apparatus with the body weight supported, sliding on a fixed track inclined at 30° to the horizontal. Their results showed high LSI in RSI post ACLR, but the subjects were over 2 years post-surgery, and the demands of the task may be less demanding with lower ground reaction forces. Considering the importance of reactive strength in jumping, change of direction and metabolic cost of running (Li, Newton, 2019, Maloney, Richards, 2017), further research is required to examine reactive strength levels in male adults during the later stages of rehabilitation and RTS following ACLR. Furthermore, it may be prudent to examine changes in SSC function following ACLR and their responsiveness to targeted rehabilitation strategies. The available evidence indicates that plyometric training is used sparingly during ACL rehabilitation (Ebert et al. , 2018); thus, more studies are required to determine if residual deficits in this fundamental physical quality are present in comparison to healthy controls.

3.4 Level of evidence, quality, and risk of bias in individual studies

All included research were controlled cohort studies; therefore, the level of evidence was 3. The included studies presented a high methodological quality (based on the modified Downs and Black scale). Risk of bias assessment (based on the PEDro scale) is presented in Table 3.2. The most frequent sources of methodological considerations were blinding of outcome assessors and participants allocation (due to obvious limitations in ACLR cohorts), distribution and adjustment for confounders, and sample size calculation. Most of the distribution of principal confounders (age, time after surgery, physical activity levels, etc.) were clearly described, except for a minority of studies where graft type used was not mentioned. This has been shown to influence important clinical outcomes (Huber et al. , 2019, Miles and King, 2019). However, all articles reported clear eligibility criteria, similar baseline across groups, complete outcome measures and adequate statistical analysis between groups for at least one key outcome.

We decided to exclude adolescent and paediatric ACLR cohorts owing to the lack of substantial high quality evidence regarding management in this population (Burland et al. , 2018, Henry et al. , 2009, International Olympic Committee Pediatric et al. , 2018, Moksnes et al. , 2012). In addition, females were not examined due to their different anthropometric, hormonal, training and kinematic features when compared to males (Capogna et al. , 2019, Ford et al. , 2003, Herzberg et al. , 2017, Hewett et al. , 2006, Lohmander et al. , 2004, Mayhew et al. , 2001, Sugimoto et al. , 2012, Walts et al. , 2008). Finally, we included only articles where a control group was present; thus, decreasing the overall pool of studies in this review. Due to the observed reductions in contralateral limb function following ACLR, using the non-injured limb as a reference and only quantifying LSI only may overestimate the functional improvements observed during rehabilitation (Patterson et al. , 2020, Wellsandt, Failla, 2017a). Instead, we included studies that compared the ACLR limb with the dominant limb of matched controls to increase the methodological quality of our review and conclusions drawn from the quantitative analysis. Finally, despite our strict criteria and the homogeneous assessment mode included in the meta-analysis, there was high statistical heterogeneity across the studies when these were analysed without differentiating graft types. Heterogeneity was significantly lowered when subgroups were created according to graft type, suggesting that studies evaluating strength outcomes should report this as part of the participant information.

3.5 Practical recommendations and future research

Deficits in knee extensor and flexor peak torque were detected in the ACLR limb of male adults in most studies even after having completed rehabilitation and returned to sports. Knee extensor strength deficits were more evident in subjects with a BPTB compared to STG grafts, where hamstring strength appeared more compromised. However, both knee extensors and flexors strength deficits have shown to reduce by implementing targeted interventions with a maximal strength emphasis adopted during rehabilitation (Królikowska, Reichert, 2019, Welling, Benjaminse, 2019).

O'Malley et al. (O'Malley, Richter, 2018) provided normative values for quadriceps and hamstring strength (i.e. 240% to 270% and 150% to 160% of their body mass on isokinetic dynamometer at 60°/s) which correlated with optimal rehabilitation status. Welling et al. (Welling, Benjaminse, 2019) suggested that quadriceps peak torque normalised to bodyweight should be > 3.0 Nm/kg at 60°/s. Therefore, it appears vital that quadriceps and hamstring strengthening should continue to be part of a rehabilitation programme until these minimum requirements are met. It is also recommended to further enhance strength beyond these values and target RFD to increase capacity in sport relevant physical qualities. Future studies should examine optimal normative strength values for proximal and distal lower limb components as well as global measures of strength (e.g. back squat, front squat, mid-thigh pull, etc.) considering the limited ability of LSI in estimating knee function and performance.

Finally, due to its high correlation with SSC performance, future research should analyse reactive strength in male adults following ACLR.

3.6 Conclusions

The findings from our synthesis of the available literature suggests that knee extensor and flexor strength deficits are still present at more than 6 months following ACLR. These appear to be influenced by graft types and importantly can be mitigated by targeted rehabilitation programs. Key rehabilitation milestones should include both absolute strength scores and LSI compared to healthy controls or pre-injury values to provide a more complete understanding of knee function and rehabilitation status. Due to the paucity of studies investigating RFD and reactive strength in this population, no definitive conclusions can be drawn between these fundamental physical determinants and rehabilitation status, and this warrants further research.

Rehabilitation following ACL reconstruction includes normalisation of maladaptive biomechanical variables in a range of dynamic tasks associated with high peak ACL strains and re-injury risk, such as jumping, landing and change of direction (Gokeler et al. , 2019). However, it is currently unclear how much of the variance in these aberrant mechanics are underpinned by sub-optimal physical capacities. Therefore, we conducted a literature search to explore the interrelationships between fundamental physical capacities and biomechanical variables during movement tasks in athletic populations following ACL reconstruction.

CHAPTER 4: LITERATURE REVIEW

Relationships between physical capacities and biomechanical variables during movement tasks in athletic populations following anterior cruciate ligament reconstruction

In this chapter we aimed to assess the interrelationships between physical capacities and kinetic and kinematic variables during movement tasks in athletic populations at the later stages of RTS following ACL reconstruction. This review was published in Physical Therapy in Sport Journal (Maestroni et al. , 2021a)

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4.0 Introduction

Sports such as soccer, basketball or rugby, require skills including pivoting, cutting, landing, or jumping and expose athletes to a high risk (incidence rates from 0.03% to 3.67% per year) of sustaining an anterior cruciate ligament (ACL) injury during their career (Lindanger, Strand, 2019, Moses, Orchard, 2012, Silvers-Granelli, Bizzini, 2017). Following ACL reconstruction, common return to sports (RTS) criteria are often achieved in cohorts with a relatively low rate of return to competitive sport (Ardern, Webster, 2011a, Webster and Hewett, 2019). Thus, current approaches to determine physical capacity and examine movement competency are considered in-adequate to identify those at a greater re-injury risk (Losciale, Zdeb, 2019b). This may be partly linked to biomechanical deficits which have been observed following ACL reconstruction, even in the presence of normalized between-limb comparisons in measures such as hop distance (Davies, Myer, 2019, Losciale et al. , 2019a), and change of direction times (King, Richter, 2018a).

Shallow knee flexion angle and pronounced knee valgus at the point of ground contact are commonly cited as a mechanism of injury, corresponding with positions of peak ACL strain (Della Villa et al. , 2020, Walden, Krosshaug, 2015). High magnitudes of knee joint loading, expressed as knee abduction moment, are thought to reflect increased knee injury risk (Fox, 2018). Knee abduction moment is influenced by whole body biomechanics during jumping and change of direction activities. In the ACL reconstructed limb, lower internal knee valgus moment, knee internal rotation angle and ankle external rotation moment, with the centre of mass less posterior to the knee are common findings across various single leg hop tests (King, Richter, 2018b). In change of direction activities, typical features include lateral flexion/rotation of the trunk and position of the centre of mass away from the intended change of direction and from the stance leg, and greater hip flexion and internal rotation at initial contact during cutting manoeuvres. Furthermore, anticipatory adjustments in the step prior to penultimate foot contact during a change of direction, can also alter kinetic and kinematic variables associated with ACL strain magnitudes (Dos'Santos et al. , 2018).

Deficits in strength (Lisee, Lepley, 2019c, Petersen, Taheri, 2014), rate of force development (RFD) (Angelozzi, Madama, 2012, Davis, Troy Blackburn, 2017, Hsieh, Indelicato, 2015, Turpeinen et al.), power (Castanharo, da Luz, 2011, O'Malley, Richter, 2018), and reactive strength (King, Richter, 2018b, Lisee, Birchmeier, 2019a) have been identified in different populations following ACL reconstruction. Therefore, rehabilitation programmes have focused on regaining symmetrical range of motion and fundamental physical capacities (i.e. strength, RFD, power, and reactive strength) (Buckthorpe and Della Villa, 2019), in addition to normalisation of maladaptive biomechanical variables in a range of dynamic tasks associated with high peak ACL strains and re-injury risk, such as jumping, landing and change of direction (Gokeler, Neuhaus, 2019). Nonetheless, the available data indicate that patients in the later stages of rehabilitation and RTS following ACL reconstruction, exhibit maladaptive movement strategies (i.e. altered neuromuscular control of the hip and knee during dynamic landing tasks) that may expose them to a greater risk of re-injury (Paterno et al. , 2010). It is currently unclear if these aberrant mechanics are underpinned by sub-optimal physical capacities, graft type, time to RTS, psychological status or altered neuromuscular control.

Mounting body of evidence suggests that an adequate level of physical capacity is required to facilitate the execution of more complex athletic skills (Cormie, McGuigan, 2011a, Cormie et al. , 2011b). However, a synthesis of the literature to determine the extent to which deficits in physical capacity affect biomechanical variables during movement execution in athletic cohorts following ACL reconstruction is unclear. Therefore, the aim of this narrative review was to examine relationships between strength, RFD, power, reactive strength, and kinetic and kinematic variables in dynamic tasks in ACL reconstructed athletes in the later stages of rehabilitation and RTS. The information included will assist clinicians, providing clear practical applications to optimise RTS.

4.1 Methodology

The lead author (LM) conducted a literature search of three electronic databases (MEDLINE, SPORTDiscus and CINHAL) on 5 March 2020. The studies were selected according to PICOS framework (Participants, Intervention, Comparison, Outcome, and Study design) (Liberati, Altman, 2009). Cohort studies investigating strength, power, RFD or reactive strength, and kinetic or kinematic variables in performance tests in participants at their later stage rehabilitation and RTS following ACL reconstruction were considered. They had to be published in peer-reviewed journals and written using English language not before 2010. The keywords "strength" or "reactive strength" or "power" or "rate of force development" were combined with the Boolean operator "AND" to keywords pertinent to kinetics, kinematics and performance measures (e.g. "biomechanics", "change of direction", "landing", etc.).

The additional inclusion criteria were: (1) participants with any graft type; (2) assessment of strength, power, RFD, or reactive strength using dynamometers or force platforms; (3) assessment of kinetic variables using force platforms; (4) assessment of kinematic variables using 3D motion capture analysis.

4.2 Physical capacity measurement

In this next section we will briefly summarise the assessment modes of physical capacities typically measured and described in ACL literature.

4.2.1 Strength

The majority of studies which have examined strength in athletic populations post ACL reconstruction included an isokinetic dynamometer at a variety of test speeds (60°/s,120°/s,180°/s, and 300°/s) for both the quadriceps and hamstring muscles (Almeida, Santos Silva, 2018, Baltaci, Yilmaz, 2012, Królikowska, Reichert, 2019, Miles and King, 2019, Mohammadi, Salavati, 2013, O'Malley, Richter, 2018, Welling, Benjaminse, 2019, Xergia, Pappas, 2013). Other testing modes included isometric MVIC on a dynamometer (Holsgaard-

Larsen, Jensen, 2014, Norouzi, Esfandiarpour, 2019, Schmitt et al. , 2015, Timmins, Bourne, 2016, Ward, Blackburn, 2018), or uniaxial load cells (Timmins, Bourne, 2016).

4.2.2 Power

The product of force (or strength) and velocity results in mechanical power; which, when divided by time, defines the rate at which work is performed (Turner et al. , 2020). The ability to express high power outputs is an important factor related to increasing performance levels (Haff and Stone, 2015). Given the components of power (P), it appears intuitive that strength (indicating high levels of force production) and speed are the main physical determinants of athletic skills, such as jumping, landing (given the need for braking force), accelerating, and changing direction (Haff and Stone, 2015, Turner, Comfort, 2020). In ACL literature power has been calculated primarily during bilateral (Castanharo, da Luz, 2011, Read, Michael Auliffe, 2020b) and single countermovement jumps (CMJ) (O'Malley, Richter, 2018). The synchronisation of kinetic and kinematic data has also been used to assess single joint power contribution, highlighting intra-limb compensation strategies commonly documented in ACL reconstructed cohorts (Baumgart et al. , 2017, Gokeler et al. , 2010, Paterno et al. , 2007).

4.2.3 Rate of force development (RFD)

RFD is defined as the ability of the neuromuscular system to produce a high rate in the rise of muscle force in the first 30-250 milliseconds (Taber, Bellon, 2016), and it is calculated as ΔForce/ΔTime, which is determined from the slope of the force time curve (generally between 0 and 250 milliseconds) (Maffiuletti, Aagaard, 2016, Rodriguez-Rosell, Pareja-Blanco, 2018). Impaired knee extension rate of torque development has been reported following ACL reconstruction (Angelozzi, Madama, 2012, Pua, Mentiplay, 2017, Turpeinen, Freitas). Assessment of RFD in a dynamic task (i.e. CMJ) has only been recently investigated (Read, Michael Auliffe, 2020b). Preliminary findings showed significant differences in eccentric deceleration RFD asymmetry between ACL reconstructed participants and healthy controls (Read, Michael Auliffe, 2020b), even greater than 9 months post-surgery which warrants further investigation to examine its validity to detect rehabilitation status and readiness to RTS (Read, Michael Auliffe, 2020b).

4.2.4 Reactive Strength

Specific qualities of strength, such as maximal eccentric strength, underpin an athlete's reactive-strength ability, allowing efficient storage and reutilisation of elastic energy during stretch-shortening cycle activities (Beattie, Carson, 2017, Suchomel, Wagle, 2019a). Quantification is typically via reactive strength index (RSI) = jump height (m) / ground contact time (sec) during a drop vertical jump (DVJ) task (Flanagan and Comyns, 2008).

Reactive strength has been assessed in ACL reconstructed cohorts during a single leg drop jump (SLDJ) (King, Richter, 2018b, Lisee, Birchmeier, 2019a). In their cohort of 156 male multidirectional sports athletes, King et al., (King, Richter, 2018b) found significant inter-limb asymmetries in RSI (21% deficits in the ACLR side, d = 0.73). This may have important clinical implications given that reactive strength significantly correlate with a reduced metabolic cost of running (running economy at 12-16 $km \cdot h^{-1}$) and change of direction performance (Li, Newton, 2019, Maloney, Richards, 2017).

4.2.5 Movement tasks assessed

Bilateral jumping and landing tasks provide valuable insights on underlying kinematic and kinetic strategy. Single leg jumping, and landing tasks increase the load that the single limb needs to withstand, with speculation that single leg dynamic tasks better reflect a measure of limb capacity (Cohen, et al. 2020). However, bilateral jumping assessments such as the CMJ or DVJ, offer more options to unload the ACL reconstructed limb than single leg tasks. This may occur via inter-limb compensatory strategies in which the uninjured limb is favoured, off-loading the previously injured side (Baumgart, Schubert, 2017, Dai et al. , 2014, Hart et al. , 2019). This can be easily quantified by the vertical ground reaction force (vGRF) generated. Furthermore, force platform assessment of CMJ performance allows identification of phase specific vGRF (eccentric, concentric and landing phase variables) as well as the time to complete these phases (Hart, Cohen, 2019).

Intra-limb compensation strategies may also be adopted in which lower peak power generation at the knee is compensated for by a higher proportion of power at proximal or distal joints (i.e. hip or ankle). These asymmetries appeared evident in sagittal plane variables such as hip extension moments (d=0.60) during the eccentric phase, and hip flexion angles (d=0.57) and ankle plantar-flexion moments (d=0.59) at the end of the stance phase during DVJ push-off (King, Richter, 2019). More pronounced inter-limb asymmetries were also evident in the frontal and transverse planes for internal knee valgus moment (d=0.5) and ankle external rotation moment (*d*=0.51) through the middle of the stance phase in ACL reconstructed athletes vs. healthy controls (King, Richter, 2019).

4.3 Relationship between strength and kinetic variables

Schmitt et al. (Schmitt, Paterno, 2015) assessed quadriceps MVIC with an isokinetic dynamometer at 60° knee flexion in relatively young participants (n=77, mean age=17 years) who completed their rehabilitation programme and were cleared to return to high-level athletic activities (cutting and pivoting). They found significant correlations between quadriceps index (involved / un-involved x 100) and kinetic variables in the bilateral DVJ from a 31 cm box. No kinetic differences were reported between participants displaying high quadriceps index (>90%) and matched controls for any limb symmetry measures. Those with low quadriceps index (<85%) demonstrated greater limb asymmetry in sagittal plane knee joint mechanics (i.e. peak external knee flexion moment ($p<0.001$), peak vGRF ($p<0.001$) and peak loading rate ($p=0.008$) during the landing phase compared to the stronger individuals. Quadriceps index was the only significant predictor (beta value= .412; $p<0.001$) for limb symmetry index (LSI) peak vGRF (R^2= .274) and for LSI loading rate (R^2= .152, beta value= .253; $p=0.04$) after controlling for graft type, presence of meniscus injury, knee pain, and knee symptoms. For LSI, peak external knee flexion moment (R^2= .501), graft type (beta value=0.295, $p=0.002$) and quadriceps index (beta value=0.510, $p<0.001$) were the only statistically significant predictors. Ward et al. (Ward, Blackburn, 2018) also observed a low negative association between MVIC and peak vGRF (r= -0.41, R^2= .17, $p=0.03$) measured during a DVJ, indicating that greater knee extension strength may minimise vGRF, although only a small amount of the variance in kinetic strategies was explained. In female athletes, lower vGRF on the ACLR limb compared to the uninvolved limb may also be present 2 years post-surgery in both the landing and takeoff phase of a DVJ (Paterno, Ford, 2007). This strategy has been associated with increased risk of ACL injury in female athletes (Hewett et al. , 2005), and has also been documented in mixed populations (Baumgart, Schubert, 2017, King, Richter, 2018b, Paterno et al. , 2011).

Quadriceps strength also appears to effect slower movements as well as rebound tasks, as Miles et al. (Miles and King, 2019) observed a relationship between quadriceps strength and kinetics during a CMJ. Knee extensor strength asymmetry explained 39% (R^2= .39; $p=0.002$) and 18% (R^2= .18; $p=0.04$) of the variation in concentric impulse asymmetry during the CMJ in the bone patella tendon bone and the semitendinosus/gracilis groups respectively. No significant relationship was shown between knee extensor strength asymmetry and eccentric impulse asymmetry in any group. Thus, targeted strategies to increase quadriceps strength appear warranted to improve aberrant kinetics during bilateral tasks.

Strength also appears to be related to kinetic parameters during single leg jumping. In young athletes cleared to return to high-level athletic activities (cutting and pivoting) following ACL reconstruction (Ithurburn et al. , 2015, Palmieri-Smith and Lepley, 2015), greater kinetic asymmetries during a single leg horizontal (Palmieri-Smith and Lepley, 2015) and vertical (Ithurburn, Paterno, 2015) landing task were more pronounced in participants with low quadriceps index compared to those with higher symmetry scores. Similarly, 78% of the variability in the lower external knee flexion moment detected in the ACL reconstructed limb during a single leg landing was explained by the knee extensor muscular capacities (R^2= .78; p<0.002) (OberlÄNder et al. , 2013). In the work of Palmieri-Smith et al. (Palmieri-Smith and Lepley, 2015), for knee flexion moment symmetry, only age (p=0.042) and quadriceps index (p=0.008) were significant predictors (R^2 change= 0.250 for quadriceps index) after controlling for age, mass, gender, time to RTS and meniscal status. Peak knee extension moment symmetry in the vertical drop land task was significantly predicted by quadriceps index (R^2 adjusted= .102; p<0.001) (Ithurburn, Paterno, 2015).

O'Malley et al. (O'Malley, Richter, 2018) found inter-limb differences in ACL reconstructed athletes in isokinetic knee-extension peak torque (d = –1.33), isokinetic knee-flexion peak torque (d = –0.19) single leg CMJ hip power contribution (d = 0.75), peak power (d = –0.47), and knee power contribution (d = – 0.37). Low to moderate correlations (r= 0.28–0.31) were also reported between isokinetic knee extension peak torque and power generation at each joint in the single leg CMJ. These data reinforce the notion that in unilateral tasks such, the ACL reconstructed limb may adopt intra-limb compensation strategies for lower peak power generation at the knee by generating a higher proportion of power at the hip. This is further evident as isokinetic knee extensor peak torque could only explain a small amount of variance in peak power generation during a single leg CMJ (O'Malley, Richter, 2018). To our knowledge, the relationship between single leg DVJ kinetic parameters and strength levels in ACL reconstructed cohorts has not been examined and further research is warranted. Indeed, evident compensatory strategies following ACL reconstruction include reduced ability to absorb and regenerate ground reaction forces upon landing (Lloyd et al. , 2020).

4.4 Relationship between strength and kinematic variables

Three dimensional kinematic data were collected using camera motion-systems and retro-reflective markers across different studies (Gokeler, Hof, 2010, Ithurburn, Paterno, 2015, Lisee, Birchmeier, 2019a, OberlÄNder, BrÜGgemann, 2013, Palmieri-Smith and Lepley, 2015, Schmitt, Paterno, 2015, Ward, Blackburn, 2018). During a bilateral DVJ from a 31 cm box, Ward et al. (Ward, Blackburn, 2018) observed lower knee-flexion angles at initial contact (p=0.03) in the ACL reconstructed limb, whereas Schmitt et al. (Schmitt, Paterno, 2015) did not find any significant between-limb kinematic difference. A low positive association was reported between knee extensor MVIC and peak knee flexion angle (r = 0.38, R^2 = 0.14, p = 0.045) (Ward, Blackburn, 2018). Due to the paucity of studies which have examined the relationship between strength and kinematic variables in bilateral dynamic tasks, further research is warranted.

Equally, only a few studies have measured associations between physical capacities and kinematic variables in unilateral dynamic tasks. Compared to matched controls, greater limb asymmetry during a single leg drop landing task in knee flexion excursion and peak trunk flexion angle was found in ACL reconstructed participants cleared to return to high-level athletic activities (cutting and pivoting) (Ithurburn, Paterno, 2015). Compared to the contralateral limb, decreased knee flexion excursion (Gokeler, Hof, 2010, Ithurburn, Paterno, 2015, Palmieri-Smith and Lepley, 2015) and increased peak trunk flexion angle was reported (Ithurburn, Paterno, 2015, OberlÄNder, BrÜGgemann, 2013). These asymmetries during landing were more pronounced in participants with low quadriceps index compared to those displaying greater symmetry. Peak trunk flexion and knee flexion excursion symmetry were significantly predicted by quadriceps index (R^2 adjusted= .153, p<0.002 and R^2 adjusted= .116, p<0.001 respectively) (Ithurburn, Paterno, 2015). This suggests that participants with low quadriceps index following ACLR adopt a strategy of greater trunk flexion when landing on the ACL reconstructed limb in a single leg drop landing task possibly to compensate for decreased knee extension strength. Similarly, in a predominantly female ACL reconstructed population, peak knee flexion angle during a single leg drop crossover hop task was predicted by peak knee extension torque (R^2= .467, beta value= 8.517; p<0.001) (Lisee, Birchmeier, 2019a), but this had no predictive value for any kinematic variable in the single leg step down task.

Collectively, the available evidence suggests that: 1) the level of correlation between knee extensor and flexor strength and kinematic variables needs to be further examined in relation to gender and task; 2) ACL reconstructed participants tend to adopt a "stiffer" landing strategy in the affected knee with less knee ROM during landing; 3) greater trunk flexion when landing in the single leg drop landing task on the injured limb may be adopted to compensate for decreased knee extension strength; 4) knee extensor deficits explain only a part of the variance in peak knee and trunk flexion angle in unilateral and bilateral tasks.

4.5 Correlation between RFD/power, kinetic and kinematic variables

Emerging research (Read, Michael Auliffe, 2020b) showed that the involved limb of male adults following ACL reconstruction (> 6 months post-surgery) displays significantly lower eccentric deceleration RFD during a CMJ compared to the uninvolved limb. While in healthy individuals, positive correlations between knee extension RTD and jump performance have been indicated (Chang et al. , 2015, de Ruiter et al. , 2006, de Ruiter et al. , 2007), the extent of this association with biomechanical variables in ACL reconstructed participants is currently lacking.

Castanharo et al. (Castanharo, da Luz, 2011) compared CMJ performance and kinetic variables between a group of ACL reconstructed adult males with semitendinosus/gracilis graft ≥ 2 years post-surgery and a control group. No significant differences in jump height were present between groups, but peak knee joint power on the injured side was 13% lower than the contralateral limb. These results highlight an "offloading" strategy of the involved limb. These results are in line with a recent systematic review and meta-analysis (Kotsifaki, Korakakis, 2019), which showed moderate evidence of a strong effect for lower power absorption in the reconstructed knee ($d = -0.98$, 95% CI −1.37 to −0.60) during the SL hop.

Read et al. (Read, Michael Auliffe, 2020b) observed that despite obtaining similar jump height in the CMJ, the ACL reconstructed group at 6-9 months post-surgery displayed significantly greater asymmetry indexes in concentric impulse (9.6 ± 5.6; 95% CI: 8.2-10.9) and concentric peak vGRF (8.0 ± 4.3; 95% CI: 6.9-9.0) than the ACL reconstructed group at >9 months post-surgery (7.4 ± 5.1; 95%: CI 6.0-8.8, and 6.6 ± 4.2; 95%: CI 5.5-7.7). No significant differences between ACL reconstructed groups in asymmetry indexes were found in eccentric deceleration impulse and peak landing vGRF. However, asymmetry of all the aforementioned kinetic variables were greater in the involved limb of the ACL reconstructed participants than in the dominant limb of healthy controls with effect sizes ranging from moderate to very large (d = 0.54-1.35).

These results are in line with recent research (Jordan et al. , 2018, Miles and King, 2019), which showed greater concentric impulse asymmetry in ACL reconstructed participants compared to healthy controls during bilateral jumping tasks. These residual deficits indicate inter-limb strategies that redistribute impulse production to favour the uninvolved side. Also, concentric impulse asymmetry index was strongly associated with rehabilitation status (p <0.001). Furthermore, similar to Mohammadi et al. (Mohammadi, Salavati, 2013) concentric peak vGRF were reduced on the ACL reconstructed side, thus indicating compensatory strategies which offload the involved limb in dynamic tasks.

During unilateral jumping, O'Malley et al. (O'Malley, Richter, 2018) found inter-limb differences in the ACL reconstructed group in single leg CMJ hip power contribution (d =0.75), jump height (d = –0.71), peak power (d = –0.47), and knee power contribution (d = – 0.37). Similar differences were also found between groups in jump height LSI (d = –1.12), jump height (d = –0.86), peak power $LSI_{modified}$ (d = –0.61), hip power contribution (d = 0.61), and knee power contribution (d = –0.40). This reinforces the notion that in unilateral tasks, the ACL reconstructed limb may adopt intra-limb compensation strategies for lower peak power generation at the knee by generating a higher proportion of power at the hip and ankle.

A recent study also analysed knee extensor early (<100ms) and late RTD (>100ms) and their association with performance tests in ACL reconstructed athletes. Birchmeier et al. (Birchmeier, Lisee, 2019) showed that both RTD_{100} and RTD_{200} had no significant correlation with amortization time in the single leg DVJ, but were moderately correlated with jump height (r= 0.391 and 0.473 respectively). Lisee et al. (Lisee, Birchmeier, 2019a) revealed that only RTD_{200} had a weak relationship with peak knee extension moment (R^2= .176, beta value= 0.066; p<0.025) in a single leg step down task. Together, the data suggests that the ability of the quadriceps to generate force rapidly may be important for lower extremity loading characteristics in hopping and jumping.

There is a paucity of studies to examine RFD/power and kinematic variables in this cohort. Lisee et al. (Lisee, Birchmeier, 2019a) showed that after ACL reconstruction, females with poorer quadriceps RFD_{100} landed with smaller knee flexion angles at initial contact during a single leg drop crossover hop task (R^2= .198, beta value= 0.721; p<0.013). Further studies are needed to investigate associations between RFD and kinematic variables in performance tests following ACL reconstruction.

4.6 Relationship between reactive strength and kinetic and kinematic variables

King et al. (King, Richter, 2018b) examined RSI and kinetic variables in performance tests in an ACL reconstructed adult male population involved in multidirectional sports approximately at 9 months post-surgery (n = 156, mean age 24.8 ± 4.8). They showed reduced RSI (21% deficit) in the injured compared to the contralateral limb ($d = -0.73$). However, no analysis was completed to identify the predictive role of RSI on kinetic variables. To our knowledge, only Birchmeier et al. (Birchmeier, Lisee, 2019) assessed the extent of the association between RSI and kinetic variables in a mixed cohort. No significant correlation was reported between RSI and amortization time in single leg DVJ. Significant correlations were found between RSI and triple hop distance ($r = 0.689$) and SLDJ height ($r = 0.609$) (Birchmeier, Lisee, 2019). These findings may appear logical considering that RSI is a measure of stretch-shortening cycle performance, hence higher scores in RSI would positively enhance performance in repetitive jumps. Further research should explore if RSI values are predictive of relevant kinematic variables in participants following ACL reconstruction during rebound tasks.

A summary of the included studies investigating the relationship between physical capacities and biomechanical variables during dynamic tasks in ACL reconstructed individuals is included in Table 4.1. Figure 4.1 depicts kinetic and kinematic variables commonly found in ACL reconstructed cohorts during the DVJ and SLDVJ.

Table 4.1 Summary of the included studies investigating the relationship between physical capacities and biomechanical variables during dynamic tasks in ACL reconstructed individuals

AUTHOR AND YEAR	PARTICIPANTS AND AGE (years)	PHYSICAL CAPACITIES TESTED	DYNAMIC TASK	MAIN FINDINGS
Schmitt (2015)	77 (males and females) Between 14 and 25	Knee extension isometric strength (MVIC) with an isokinetic dynamometer	DL DVJ Participants were positioned on the top of a 31-cm box and were instructed to drop off the box simultaneously with both feet, landing with each foot onto separate force platforms and then to perform a maximal effort vertical jump	**KINETIC** Quadriceps index was the only significant predictor (beta value= .412; $p<0.001$) for limb symmetry index (LSI) peak vGRF (R^2= .274) and for LSI loading rate (R^2= .152, beta value= .253; $p=0.04$) after controlling for graft type, presence of meniscus injury, knee pain, and knee symptoms. For LSI, peak external knee flexion moment (R^2= .501), graft type (beta value=0.295, $p=0.002$) and quadriceps index (beta value=0.510, $p<0.001$) were the only statistically significant predictors **KINEMATIC** No significant between-limb kinematic difference
Ward (2018)	28 (males and females) 22.4 ± 3.7	Knee extension isometric strength (MVIC) with a dynamometer	DL DVJ Participants performed a jump-landing task from a 30-cm box positioned at 50% of the participant's height from the front edge of the force plates. They jumped forward off	**KINETIC** Low negative association between MVIC and peak vGRF (r=-0.41, R^2=0.17, p=0.03) **KINEMATIC** Low positive association was reported between knee extensor MVIC and peak knee flexion angle (r=0.38, R^2=0.14, p=0.045)

			the box to a double-legged landing with 1 foot on each force plate and then immediately jumped vertically as high as possible	
Miles (2019)	Males only 44 = 22BPTB + 22STG BPTB 23.4 ± 4.4 STG 26.1 ± 4.4	Isokinetic concentric knee extension and flexion strength (60°/s)	DL CMJ Participants were instructed to maintain hands placed on iliac crests and to jump as high as they could with knees extended during the flight phase	**KINETIC** Knee extensor strength asymmetry explained 39% (R^2= .39; *p*=0.002) and 18% (R^2= .18; *p*=0.04) of the variation in concentric impulse asymmetry during the CMJ in the bone patella tendon bone (BPTB) and the semitendinosus/gracilis (STG) groups respectively. No significant relationship was shown between knee extensor strength asymmetry and eccentric impulse asymmetry in any group
Ithurburn (2015)	103 (males and females) 17.4	Knee extension isometric strength (MVIC) with an isokinetic dynamometer	SL drop land Participants stood at the edge of a 31-cm box on the limb being tested and were instructed to drop off of the box and land on a force platform on the same limb. Participants were required to maintain a controlled landing for at least 3 seconds after landing	**KINETIC** Quadriceps index was a significant predictor of peak knee extension moment LSI (R^2 adjusted = .102; *p*<0.001) **KINEMATIC** Quadriceps index was a significant predictor of knee flexion excursion LSI (R^2 adjusted = .116; *p*<0.001) and peak trunk flexion angle LSI (R^2 adjusted = .153; *p*<0.001)
			SL hop	**KINETIC**

Palmieri-Smith (2015)	66 (males and females) 14-30	Isokinetic concentric knee extension strength (60°/s)	Participants stood on their test leg and hopped forward as far as possible landing only on the same leg	For knee flexion moment symmetry, only age (*p*=0.042) and quadriceps index (*p*=0.008) were significant predictors (R^2 change= 0.250 for quadriceps index) after controlling for age, mass, gender, time to RTS and meniscal status. Peak knee extension moment symmetry in the vertical drop land task was significantly predicted by quadriceps index (R^2 adjusted= .102; *p*<0.001) **KINEMATIC** Meniscal status, mass, and time to return to activity were not found to be significant predictors of biomechanical symmetry for peak knee flexion angle ($p > 0.05$), while age ($p = 0.013$) and gender ($p = 0.049$) did influence values. After controlling for all these variables in the model quadriceps index was also a significant predictor for knee flexion angle symmetry (R^2 change = .285)
Oberlander (2013)	10 (gender not specified) 28 ± 7	Isometric strength (MVIC) with a custom-built dynamometer with a strain gauge load cell	SL hop test Participants performed a modified single leg hop test for distance, keeping their hands on their hips. This hop was performed with one leg over a given distance of 0.75 x body height. Landing had to be on the force plate within a target area corresponding to the given distance ±5 cm.	**KINETIC** 78% of the variability in the lower external knee flexion moment detected in the ACLR limb was explained by the knee extensor muscular strength (R^2= .78; *p*<0.002)
O'Malley	Males only		SL CMJ	**KINETIC**

(2018)	118 Patellar tendon 23.6 ± 5.8	Isokinetic concentric knee extension and flexion strength (60°/s)	Participants were instructed to stand with 1 foot on the force plate and the free leg behind at approximately 90°. With their hands on their iliac crests, they were asked to complete an SL CMJ, jumping as high as possible.	Low to moderate correlations (*r*= 0.28–0.31) were reported between isokinetic knee extension peak torque and power generation at each joint
Lisee (2019)	52 (males and females) 22.6 ± 4.4	Knee extension isometric strength (MVIC) and RTD with an isokinetic dynamometer	SL step down Participants were instructed to step down off a 30-cm box onto the force plate and continue walking forward as if stepping off the final step of a set of stairs. SL drop crossover hop Participants were instructed to jump off the involved limb from a 30 cm box landing onto the force plate with the same limb. Immediately after landing on the force plate, participants hopped as far as possible diagonally along a line projecting 45° from the center of the	**KINETIC** Peak knee extension torque is the only predictor of peak knee extension moment (R^2= .404) during SL drop crossover hop landing. RTD200 had a weak relationship with peak knee extension moment (R^2= .176, beta value= 0.066; p<0.025) during the SL step down **KINEMATIC** Peak knee flexion angle was predicted by peak knee extension torque (R^2= .467, beta value= 8.517; p<0.001)) Individuals with poorer quadriceps RFD100 landed with smaller knee flexion angles at initial contact (R^2= .198, beta value= 0.721; p<0.013) during SL drop crossover hop landing

			force plate	
Birchmeier (2019)	52 (males and females) 22.9 ± 5.0	Knee extension isometric strength (MVIC) and RTD with an isokinetic dynamometer RSI measured during a SLDVJ	SL hop Participants hopped as far as possible from the designated starting line on one leg SL triple hop for distance Participant hopped 3 consecutive times on the same leg as far as possible	**KINETIC** Peak knee extension torque, RTD100 and RTD200 had no significant correlation with amortization time in the SLDJ

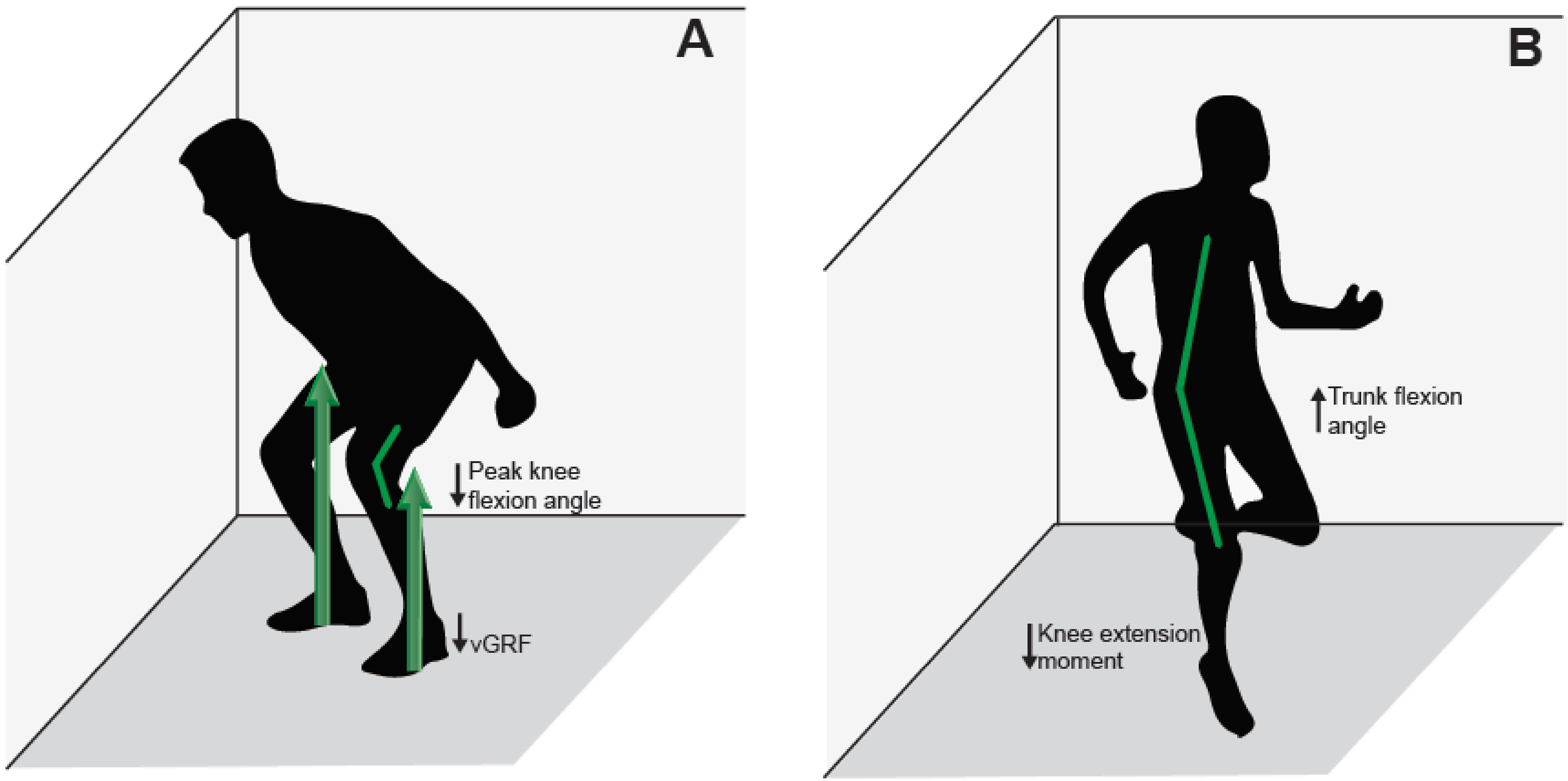


Figure 4.1 Example of kinetic and kinematic variables commonly found in ACL reconstructed cohorts during the (A) drop vertical jump (DVJ) and (B) single leg drop vertical jump (SLDVJ)

4.7 Practical applications and recommendations for future research

Deficits in knee extensor torque are commonly reported in ACL reconstructed cohorts and are associated with inter-limb and intra-limb compensation strategies indicative of greater re-injury risk (Ithurburn, Paterno, 2015, Lisee, Birchmeier, 2019a, Miles and King, 2019, O'Malley, Richter, 2018, OberlÄNder, BrÜGgemann, 2013, Paterno, Ford, 2007, Paterno, Schmitt, 2010, Schmitt, Paterno, 2015). Specifically, in bilateral tasks inter-limb compensation strategies are adopted to reduce GRF on the ACL reconstructed limb, whereas in unilateral tasks intra-limb "offloading" strategies reduce the peak vGRF and power contribution at the knee by generating more power at the hip and ankle joint. Knee extensor strength deficits explain part of the variance in kinematic variables such as peak knee (R^2=14% to 46.7%) and trunk flexion angles, and in kinetic variables such as, peak knee extension moment (R^2= 40.4% to 78%), peak vGRF (R^2=17% to 27.4%) and concentric impulse asymmetry (R^2=18% to 39%) in jumping tasks. Concentric impulse asymmetry index during a CMJ is strongly associated with rehabilitation status, with lower values indicating better function (Miles and King, 2019) and is related to quadriceps strength [8]. Therefore, it appears of the utmost importance that strategies to increase maximal quadriceps strength are an integral component of rehabilitation. Large deficits in peak knee extension strength are commonly reported in ACL reconstructed participants at the later stages of rehabilitation and RTS (Johnston et al. , 2020, Maestroni, Read, 2021b). Thus, sports and healthcare professionals are encouraged to adopt specific exercise selection, dosage and progressions in line with current best practice (2009, Morton, Colenso-Semple, 2019). Future research is warranted to examine global strength capacity following ACL reconstruction to determine if stronger associations with biomechanical variables during movement tasks are present. For detailed information regarding practical applications to return athletes to high performance we recommend recently published articles (Buckthorpe, 2019, Buckthorpe and Della Villa, 2019, Maestroni, Read, 2020, Welling, Benjaminse, 2019).

Our understanding of how residual deficits in power and RFD during single and multi-joint movements and their relationships with kinetic and kinematic variables is limited and should be the focus of future studies. Similarly, due to its association with stretch-shortening cycle performance, relationships between reactive strength and biomechanical variables should also be examined in athletic populations following ACL reconstruction. In addition, the importance of monitoring contralateral limb capacity during rehabilitation (i.e. concentric/eccentric strength, RFD and RSI) should not be underestimated due to the potential for deconditioning which may increase injury risk and reduce an athlete's readiness to re-perform.

When interpreting the conclusions of this review, it should be considered that we did not perform a systematic review. Thus, specific inclusion criterion was not applied and the level of evidence, methodological quality and risk of bias in individual studies were not assessed in this manuscript. The current narrative review provides a synthesis and critique of the literature in this broad research area, and thus further opportunities for critical analysis.

4.8 Conclusions

This article examined the degree of association between fundamental physical qualities, such as strength, rate of force development/power and reactive strength and biomechanical variables during movement tasks in participants following ACL reconstruction. The available data suggests that quadriceps strength and RTD, explain a moderate portion of the variance in aberrant kinetic and kinematic strategies commonly detected in ACL reconstructed cohorts at who are during the later stages of rehabilitation and RTS. The concepts expressed in this article may help clinicians to optimise rehabilitation outcomes following and reduce re-injury risk.

The data gathered from our reviews were used to inform our experimental work, which then consisted in exploring a broader range of kinetic variables that could provide an indication of SSC function and movement strategy. Also, particular attention was given to the SLDJ in which deficiencies could be more representative of increased subsequent re-injury risk.

CHAPTER 5: METHODS, PROCEDURES AND STATISTICS

In this methods chapter, procedures and statistical tests used in the different empirical studies (chapter 6, 7 and 8) of this thesis are described. This allows the reader to fully comprehend the methodological rationale underpinning each analysis conducted. This chapter will be referred to throughout the thesis to avoid unnecessary repetition.

5.1 Procedures

This empirical research assessed physical performance capacities and the relevant movement kinetics and kinematics in a cohort of athletes during rehabilitation following ACLR and prior to RTS. These variables were assessed at different time points (from 16 weeks until discharge) during the post-surgical period. Participants were also monitored throughout their respective competitive RTS season in order to record any subsequent injuries as part of the National Sports Medicine Program at Aspetar Orthopaedic and Sports Medicine Hospital (inclusive of a 12 month follow up period).

5.1.1 Biomechanical assessment

Abnormal movement patterns or biomechanical asymmetries of the lower limb are hypothesized as risk factors for subsequent injuries as well as suboptimal sports performance. To investigate these factors, movement kinetics and kinematics were obtained during sport relevant movements using an isokinetic dynamometer (Biodex Medical Systems, Shirley, New York, USA), force platforms (Force Decks, Vald Performance, Australia) and motion analysis software (Noraxon, USA). The battery of tests is described below.

5.1.2 Isokinetic knee extension and flexion strength

Maximal quadriceps knee extension peak torque (Quad PT Rel) and hamstring flexion peak torque (HS PT Rel) relative to body mass ($N.m.kg^{-1}$) were measured using an isokinetic dynamometer. Players were in a seated position with the hip flexed to 90°. Five repetitions of concentric knee extension and flexion were performed at 60°/s with the highest peak torque value recorded (Undheim et al. , 2015). Peak torque values were reported as a percentage of the individual's body mass. Procedures were explained to participants following which they completed 3 practice repetitions. Testing then commenced after 60s. Limb order was randomized. The dominant limb of healthy controls was defined as the preferred kicking leg. Standardized, vigorous verbal encouragement was provided throughout. Each participant had previous experience of isokinetic testing.

5.1.3 Countermovement Jump (bilateral/single)

Participants were instructed to stand fully upright, hands-on hips, and align their feet on a synchronized dual force plate system. Prior to the initiation of the test, each individual was instructed to remain motionless for a minimum of three seconds to ensure a stable baseline of force at body weight was obtained. Players then performed a downward motion (descent phase) until they reached their preferred self-selected depth, before rapidly reversing the motion by triple extending at the hip, knee, and ankle. The aim of the task was to achieve their maximal vertical displacement of the centre of mass. Hands remained on hips throughout and no bending of the knees was permitted whilst airborne. The procedures were replicated for the SLCMJ, except the non-test leg was positioned with the hip and knee at 90º and no obvious swinging was allowed to minimize contralateral propulsion. Limb order was randomized. Three trials were performed with a 30 s rest period between each jump.

All data were recorded at a sampling rate of 1000 Hz. The initiation of the jump was defined by a 20 N change from body weight calculated during the quiet standing period and the instant of take-off, when the total vertical force dropped below 20 N.

5.1.4 Single leg drop vertical jump

Athletes began in a unilateral stance and then stepped directly off a 15-cm box, landing with the same leg on a force plate (ForceDecks v1.2.6109, Vald Performance, Albion, Australia). Following ground contact, a vertical rebound jump was immediately performed. Instructions were to minimize the time spent on the ground and jump as high as possible. Hands remained on hips throughout the test. Bending of the test leg whilst airborne was not permitted. Three practice attempts were performed on each limb followed by a 60 s rest period. Players then completed three recorded trials with 30s of rest between each. The limb order was randomized. Ground reaction force data were sampled at 1000 Hz and smoothed using a fourth order recursive low-pass Butterworth filter with a cut off of 30 Hz built into a customized Microsoft Excel® (v16.0) spreadsheet.

To measure kinematics, inertial measurement unit (IMU) sensors (Noraxon myoMOTION™ System, Scottsdale, USA) sampling at a rate of 200Hz were placed according to the rigid body model used in the Noraxon MR3 software (Noraxon myoMOTION™ System, Scottsdale, USA). Sensors were positioned on the pelvis and bilaterally on the lateral thighs, shanks, and mid-foot, with the X-coordinate on the sensor label having a superior orientation (showing up to the sky/ceiling), except for the foot sensors, where the X-coordinate was pointing distally (toward the toes). Velcro straps and tape were used to fix the sensors. The upright position was used to carry out the calibration of the model using the neutral/zero method which assumes that all joints are at zero position in a normal upright standing pose. Joint and individual sensor orientation angles and angular velocities were recorded and further processed using MR3 software.

5.1.5 Total score of athleticism (TSA)

A composite score of physical capacities was derived by for each player by averaging standardized scores from different physical performance outputs. To calculate the z – score of each test, the following formula was used: z – score = (player score – cohort mean) / cohort standard deviation. Finally, the TSA was calculated by averaging all z-scores (Turner et al. , 2019).

5.2 Statistics

The statistical procedures used to analyze our data are described below

Between groups differences: independent samples *t*-test (for normally distributed data) or Mann–Whitney U (for non-normally distributed data) tests were used to examine differences between two groups. ANOVA (for normally distributed data) or Kruskal–Wallis (for non-normally distributed data) were used to examine difference between more than two groups.

The *independent t-test* uses the t-statistic to establish whether two means collected from independent samples differ significantly. Assumptions include: continuous variables, independent scores, normally distributed data, homogeneity of variance

Within groups differences: paired-samples tests (for normally distributed data) or Wilcoxon Rank Sum Test (for non-normally distributed data) were used to detect differences within the same group

The *paired-samples t-test* uses the t-statistic to establish whether two means collected from the same sample differ significantly. Assumptions include: continuous variables, normally distributed data

Interaction effect: Two-way repeated measures ANOVA was used to examine interaction of time and/or injury (performance on the injured limb) for each test variable in the ACL group.

A *Two-way repeated measures ANOVA* is used in studies in which a dependent variable was measured over two or more time points, or when subjects have undergone two or more conditions.

Distribution of categorical variables: Chi-squared (χ^2) analysis was used to investigate the interaction between limbs and/or groups and SSC category.

Chi-square is a statistical test used to compare observed results with expected results. The purpose of this test is to determine if a difference between observed data and expected data is due to chance, or if it is due to a relationship between the categorical variables studied.

Group membership prediction: binary logistic regression was used to examine the predictive ability of the TSA in identifying group membership (ACL reconstructed or uninjured group).

Binary logistic regression predicts the membership of only two categorical outcomes (in our case ACL reconstructed or uninjured group membership). A logit transformation is applied on the odds - that is, the probability of success divided by the probability of failure – in the form of a logistic regression equation, commonly known as log odds.

To ease results interpretation, log odds can be transformed into an odds ratio (OR), exponentiating the beta estimates.

A *odds ratio* (Exp(B) in the SPSS output) is an indicator of the change in odds resulting from a unit change in the predictor.

If Exp(B) > 1, then percentage = (Exp(B) – 1) *100. The comparison category increases in relation to the outcome variable

If Exp(B) < 1, then percentage = (1 - Exp(B)) *100. The comparison category decreases in relation to the outcome variable

Reliability scores: between trial reliability was analyzed using a 2-way random effects intraclass correlation coefficient [ICC(2,1)] (Koo and Li, 2016) with 95% confidence intervals (CI). The ICCs were analyzed as both single and average measures. Coefficient of variation (CV%) and 95% confidence intervals (95%CI) were calculated using the formulas: (SD/Mean)*100 and [(Mean/√(2*n)]*1.96 respectively. Standard error of measurement (SEM) was calculated with the following formula: SD*√(1-ICC). Reliability scores were categorized as "acceptable" if the CV was ≤ 10% (not acceptable if CV > 10%) (Turner et al. , 2015), and were further categorized as "excellent" if ICC was > 0.90, "good" between 0.75 and 0.90, "moderate" between 0.50 and 0.75, and "poor" < 0.50 (Koo and Li, 2016).

The coefficient of variation (CV) is a statistical measure of the relative dispersion of data points in a data series around the mean [CV% = (SD / MEAN) *100].

Intraclass correlation coefficient (ICC) is a measure of reliability that reflects both the degree of correlation and agreement between measurements. Ten forms of ICC based on the model (1-way random effects [1], 2-way random effects [2], or 2-way fixed effects [3]), the type (single rater/measurement [1] or the mean of k raters/measurements [k]), and the definition of relationship considered to be important (consistency or absolute agreement) have been defined (McGraw and Wong, 1996).

Standard error of measurement (SEM) estimates the variation around a "true" score for an individual when repeated measures are taken. It is calculated using the following formula: SD*√(1-ICC).

A Confidence Interval (CI) provides upper and lower limits that capture the range of values around the true but unknown population. The 95% CI value is a range of values that you can be 95% confident contains the true mean of the population [(Mean/√(2*n)]*1.96]

Effect size (ES) is a dimensionless estimate (i.e., a measure with no units) that indicates both direction and magnitude of the treatment effect (Israel and Richter, 2011)

Among the numerous different measures of effect size, the main effect sizes based on differences between means used in this thesis were Cohen's *d* (for samples > 30) and Hedge's *g* (for samples < 30). Thresholds to quantify the magnitude of the difference have been provided to assist researchers in interpreting the results. In this thesis we used the following: d = 0.2 “small” effect, d = 0.5 “moderate” effect, and d = 0.8 “large” effect.

Symmetry scores: symmetry index (100-[(MAX – MIN)/TOTAL*100]) was used to calculate inter-limb differences during bilateral tests (Shorter et al. , 2008), whereas the formula used for calculating inter-limb differences in unilateral tests was the Standard Percentage Difference (100- (100/MAX *MIN*-1+100)) (Bishop et al. , 2018).

Correlation between variables: Pearson (for normally distributed data) and Spearman's rank (for non-normally distributed data) correlation coefficients (r) were used to determine whether variables had strong associations to each other, and thus may be reporting similar information ($r > 0.8$).

The *Pearson correlation* measures the strength of the linear relationship between two variables. Values range between − 1 and 1, where 0 is no correlation, 1 is total positive correlation, and − 1 is total negative correlation.

CHAPTER 6: Empirical STUDY 1

A comparison of strength and power characteristics prior to anterior cruciate ligament rupture and at the end of rehabilitation prior to return to sport in professional soccer players

In this chapter we examined changes in strength and power characteristics at the time of RTS relative to pre-injury baseline data and healthy matched controls. This study was published in Sports Health Journal

Maestroni, L., Turner, A. N., Papadopoulos, K., Cohen, D., Sideris, V., Graham-Smith, P., & Read, P. (2023). A comparison of strength and power characteristics prior to anterior cruciate ligament rupture and at the end of rehabilitation in professional soccer players. Sports Health.

6.0 Introduction

Anterior cruciate ligament (ACL) injuries in elite soccer players incur a high burden (Bahr et al. , 2018), with substantial time-loss and economic cost (Eggerding et al. , 2021). This traumatic event often results in surgical reconstruction and return to sport (RTS) time is on average ~ 8 months (Schiffner, Latz, 2018). Although most elite athletes (83%) return to their pre-injury level of competition following ACL reconstruction (Lai, Ardern, 2018a), this is often accompanied by an increased risk of ipsilateral (King et al. , 2021a) and contralateral (King et al. , 2021b) injury, early onset of posttraumatic osteoarthritis, and sports performance deterioration (Culvenor, Collins, 2015, Lai, Ardern, 2018a, Lai, Feller, 2018b, Larsen, Jensen, 1999).

Strength and power are reduced following ACL reconstruction (Maestroni, Read, 2021b). Strength assessment has commonly included isokinetic testing of knee extension and flexion peak torque, with established excellent reliability scores documented (Anderson, Browning, 2016, Impellizzeri et al. , 2008, Sole et al. , 2007). Deficits in peak knee extension and flexion torque are commonly displayed in the ACL reconstructed limb compared to the uninvolved side and healthy controls after rehabilitation at the time of RTS (Johnston, McClelland, 2020, Maestroni, Read, 2021b). In addition, jump performance is often used to quantify dynamic multijoint force production and can discriminate rehabilitation status (Miles and King, 2019, O'Malley, Richter, 2018). Countermovement jump (CMJ) performance variables can help practitioners to quantify neuromuscular qualities that underpin movements inherent to soccer such as sprinting, jumping, and change of direction (Haff and Stone, 2015). However, it has been suggested that single leg dynamic tasks are more representative of limb strength due to their higher relative force demands(Cohen D, 2020), whereas bilateral jumping and landing tasks occur at a higher velocity. Furthermore, compensation strategies are restricted to inter-joint in unilateral movements, whereas bilateral jumping can provide more options to unload the ACL reconstructed limb via both inter-joint and interlimb (Maestroni, Papadopoulos, 2021a). The differing demands of the bilateral and unilateral tasks may reveal specific deficits, warranting the inclusion of both in the assessment of neuromuscular performance for athletes during rehabilitation aiming to return to a high level of competition.

Research (Jordan, Aagaard, 2018, King, Richter, 2021a, b, King, Richter, 2018b, King, Richter, 2019, Miles and King, 2019, O'Malley, Richter, 2018, Read et al. , 2020a, Read, Michael Auliffe, 2020b) assessing strength and power characteristics in athletes following ACL reconstruction has been limited mostly to cross-sectional studies at single time points or around the time of RTS. Residual deficits in vertical jump height, lower limb power, and reactive strength appear to be present following ACL reconstruction (Lloyd, Oliver, 2020, O'Malley, Richter, 2018, Read, Davies, 2020a). Lower quadriceps strength and reduced plyometric ability have also displayed associations with increased risk of contralateral reinjury (King, Richter, 2021a, b). However, the available research has used the contralateral limb or values from matched controls to determine if deficits are present. There is potential for deterioration of the uninvolved contralateral limb following surgery due to deconditioning/lack of exposure (Wellsandt, Failla, 2017a). Without pre-injury baseline physical characteristics, it is impossible to determine if athletes have returned to previous strength and jump performance values. It is also unknown if matched controls provide an accurate representation of baseline / pre-injury performance. A prospective study monitoring strength and power qualities from tests that are commonly used as part of RTS assessment in elite soccer players before and after ACL rupture and reconstruction may help guide performance recovery and determine the accuracy of proxy measures, including the uninvolved limb and comparison values of healthy controls.

Our aim was to examine changes in strength and power performance following the completion of rehabilitation at the time of RTS compared to pre-injury baseline data and compared to healthy matched controls. Using these data, we examined how pre-injury benchmark data can be used to guide performance recovery and inform physical readiness as part of RTS decision making. Our specific research questions included: 1) to what extent performance metrics are recovered at the time of RTS following ACL reconstruction; and 2) how accurate is the use of; a) the contralateral limb; and b) group / control normative data as proxy measures for determining performance recovery when pre-injury data exist.

6.1 Methods

6.1.1 Participants

Twenty soccer players (24.7 ± 3.4 years; height = 175.3 ± 7.0 cm; weight =69.5 ± 10.7 kg) participating in the Qatar Stars and Gas Leagues attended a periodic health evaluation between 2017 and 2019, and subsequently went on to sustain an ACL rupture before undergoing ACL reconstruction (ACL group). The majority of ACL grafts were bone-patella-tendon bone (80%), with the remaining players (20%) all semitendinosus and gracilis hamstring tendon grafts. Only participants with no history of previous ACL injury / surgery, or other knee ligament or cartilage injury / surgery of either the operated or non-operated leg at the time of the periodic health evaluation were included. All athletes were treated at the same Orthopaedic and Sports Medicine Hospital. Rehabilitation was delivered 5 days per week and divided into early, intermediate, and advanced phases. The focus of the early phase was on controlling swelling, restoring range of motion and activation of the knee extensor and flexor muscles. The goal of the intermediate and advanced phases was to optimise muscle strength, proprioception, and neuromuscular control, and complete a phased running progression program. On completion of these phases, players took part in an on-field sports specific training and conditioning block.

We also recruited thirty-five (uninjured) controls (23.8 ± 2.8 years; height = 173.8 ± 5.4 cm; weight = 71.6 ± 6.3 kg) from the same leagues who attended pre-season screening at the national sports medicine institution and were randomly selected from a pool of 300 athletes. Inclusion was based on having no history of ACL injury and being free from any severe injury (defined as > 28 days' time-loss) in the previous 12 months, verified via a national injury audit. Clubs competing in the stated leagues within Qatar regularly complete formalised strength and conditioning including resistance training, speed, agility and plyometrics. Before participating, all participants provided informed written consent and ethical approval was provided (IRB: F2017000227).

6.1.2 Experimental approach to the problem

To address our stated aims, we separated the study into 4 components. ***In part 1,*** we compared strength and power characteristics of the ACL group to the uninjured group using both the pre-injury (baseline) data and performance following the completion of rehabilitation of the ACL group. Pre-injury baseline data are not commonly available, forcing clinicians to instead use either peers/published data and or the contralateral limb as proxy benchmarks following ACL reconstruction (Maestroni, Read, 2021b), but the former has not been explored. In ***part 2***, we monitored the trajectory of strength and power performance of the uninvolved limb in the ACL group by comparing isokinetic and SLCMJ assessment scores at two time points: pre-injury and at the end of rehabilitation prior to RTS. Conflicting evidence is available about the detrimental effect of ACL reconstruction and subsequent deconditioning on the uninvolved limb (Lisee et al. , 2019b, Rohman et al. , 2015, Wellsandt, Failla, 2017a). Currently, no study has conducted an assessment of strength and power characteristics of the uninvolved limb before and after ACL reconstruction following structured full time rehabilitation. In ***part 3,*** we measured the effect of ACL reconstruction and rehabilitation on the injured limb by comparing isokinetic and SLCMJ performance scores at two time points: pre-injury and at the end of rehabilitation, following sports specific reconditioning prior to RTS. Finally, in ***part 4***, we investigated the effect of ACL reconstruction on bilateral CMJ performance by comparing pre-injury and RTS values.

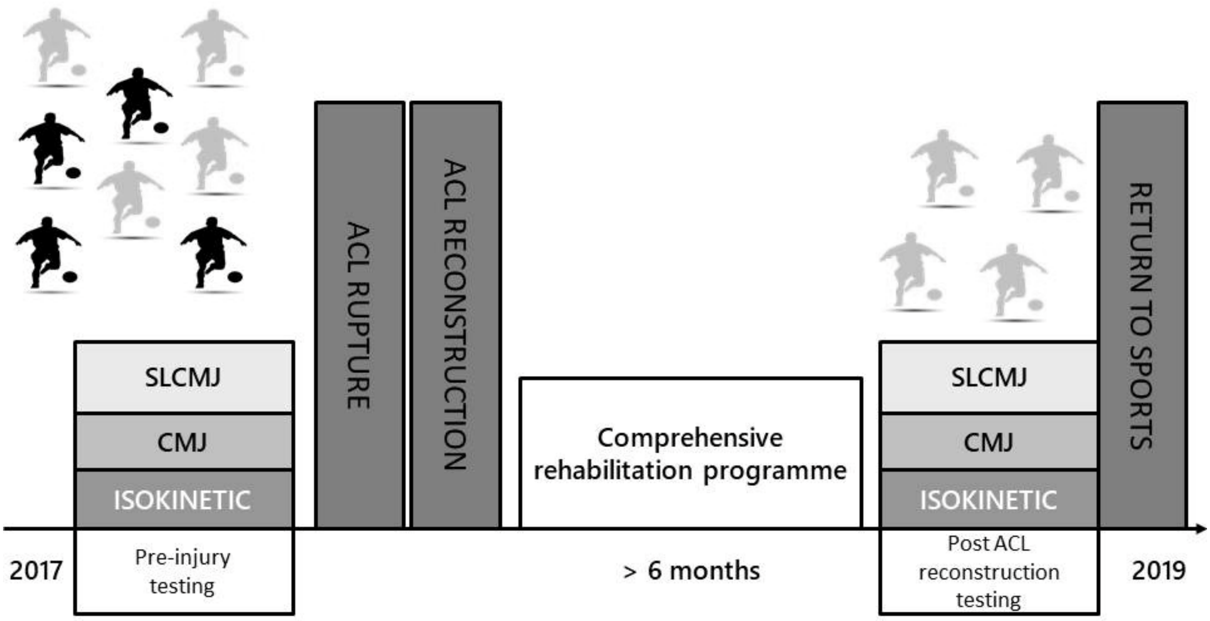


Figure 6.1 Schematic representation of the study design. Uninjured players (black). Injured players (grey).

A schematic diagram of our study is represented in Figure 6.1. A test battery consisting of isokinetic strength assessment, CMJ, and SLCMJ was performed. The ACL reconstructed cohort was screened 33.9 ± 29.6 weeks before the ACL rupture, and assessed at the end of rehabilitation prior to RTS (30.3 ± 7.2 weeks post-surgery). Players completed a standardized warm up consisting of 5 minutes on a cycle ergometer, bilateral and unilateral bodyweight squats, and bilateral CMJs at 50, 75 and 100% maximum effort (Read et al. , 2021). Test conditions and procedures were replicated at each assessment.

6.1.3 Procedures

Isokinetic knee extension and flexion strength

For the detailed testing procedures used for isokinetic knee strength refer to Chapter 5

Five repetitions of concentric knee extension and flexion were performed at 60°/s with the highest peak torque value recorded (Undheim, Cosgrave, 2015). Peak torque values were reported as a percentage of the individual's body mass. Procedures were explained to participants following which they completed 3 practice repetitions. Testing then commenced after 60s. Limb order was randomized. The dominant limb of healthy controls was defined as the preferred kicking leg. Standardized, vigorous verbal encouragement was provided throughout. Each participant had previous experience of isokinetic testing and all tests were conducted by the same physiotherapist with > 5 year's experience in the relevant test procedures.

Countermovement Jump (bilateral/single)

For the detailed testing procedures used for CMJ and SLCMJ refer to Chapter 5

We selected three outputs, which are commonly reported in jump performing testing of healthy athletes and which can also be estimated using other lower cost technologies than force platform. Jump height was calculated from the impulse-momentum relationship derived take off velocity and equation of constant acceleration (velocity at take-off squared divided by 2*9.81 ($v^2/2g$). Peak power was measured and normalized to bodyweight Watt$^{\cdot kg-1}$ (Peak

Power Rel) during the propulsion phase. Reactive strength index modified (RSImod) was calculated by dividing jump height by contraction time (determined from movement onset to time to take off (Suchomel et al. , 2015).

Intraday reliability analysis was conducted on baseline pre-injury scores of the ACL group. The between trial reliability was analyzed using a 2-way random effects intraclass correlation coefficient [ICC(2,1)] (Koo and Li, 2016) with 95% confidence intervals (CI). The ICCs were analyzed as single measures. Coefficient of variation (CV%) and 95% confidence intervals (95%CI) and Standard error of measurement (SEM) were also calculated. Reliability scores were categorized as acceptable if the CV was ≤ 10% (Turner, Brazier, 2015), and were further categorized as "excellent" if ICC was > 0.90, "good" between 0.75 and 0.90, "moderate" between 0.50 and 0.75, and "poor" < 0.50 (Koo and Li, 2016).

CMJ height, relative peak power and reactive strength displayed "excellent" reliability with ICC ranging from 0.945 to 0.978, and CV between 2.1 and 8.6% (Table 6.1). SLCMJ height, RSImod and jump height symmetry displayed "excellent" reliability, with ICCs ranging from 0.901 to 0.960 and CV between 4.2 and 5.9 (Table 6.1). Relative peak power showed CV < 10%, and ICC between 0.781 and 0.860.

Table 6.1 Intra-class correlation coefficients (ICC), coefficient of variation (CV%) and standard error of measurement (SEM) of the performance variables assessed during the bilateral countermovement jump (CMJ) and single leg countermovement jump (SLCMJ)

Test	Variable	CV % (95%CI)	ICC (2,1) (95% CI)	SEM
CMJ	Jump Height	2.7 (1.6 -3.8)	0.978 (.922- .994)	1.4
CMJ	Peak Power Rel	2.1 (1.2 – 3.0)	0.966 (.883- .991)	1.4
CMJ	RSI Mod	8.6 (5.0 – 12.2)	0.945 (.875-.976)	0.0
SLCMJ	Jump Height INV	5.2 (3.2 – 7.1)	0.96 (.876- .988)	1.0
SLCMJ	Peak Power Rel INV	6.3 (3.9 – 8.7)	0.781 (.424- .928)	2.2
SLCMJ	RSI Mod INV	10.8 (6.6 – 14.9)	0.907 (.724- .971)	0.0
SLCMJ	Jump Height UNINV	5.9 (3.6 – 8.1)	0.933 (.802-.979)	1.0
SLCMJ	Peak Power Rel UNINV	4.0 (2.5 – 5.5)	0.860 (.612- .955)	1.4
SLCMJ	RSI Mod UNINV	8.0 (4.9 – 11.1)	0.893 (.686- .966)	0.0
SLCMJ	Jump height symmetry	4.2 (2.4 - 6.0)	0.901 (.713- .968)	4.6

INV (involved limb), UNINV (uninvolved limb)

6.1.4 Statistical analysis

The distribution of the data was checked using the Shapiro-Wilk normality test. Descriptive statistics (mean ± SD) for all variables were calculated. Percentage changes from pre-injury to post ACL reconstruction were calculated for each player using the percentage difference and then averaged.

In ***part 1***, an independent samples *t*-test or Mann–Whitney U tests were used to examine differences in anthropometrics and physical performance variables between ACL and uninjured group.

For ***parts 2, 3, and 4*** paired-samples tests or Wilcoxon Rank Sum Test were used to detect statistical differences between pre-injury and post-surgery physical performance variables. The Two-way repeated measures ANOVA was used to examine the influence and interaction of time and/or injury (performance on the injured limb) for each test variable in the ACL group.

In all parts, Bonferroni correction was applied to reduce the risk of type I error with multiple statistical tests (adjusted $\alpha = 0.025$ and $\alpha = 0.017$ for isokinetic dynamometry and dual force plate system derived variables respectively). Hedges *g* effect sizes (ES) with 95% confidence intervals were calculated to interpret the magnitude of these differences with the following classifications: standardized mean differences of 0.2, 0.5, and 0.8 for small, moderate, and large effect sizes, respectively (Turner et al. , 2021b). Significance was set at $p < 0.05$. Data processing and descriptive statistics were processed using SPSS® (V.25. Chicago Illinois).

6.2 Results

6.2.1 Part 1: strength and power characteristics of the ACL reconstructed group vs healthy matched controls

Baseline (pre-injury) anthropometric, strength and power characteristics of the ACL reconstructed group were not significantly different to healthy matched controls (see Table 6.2).

Table 6.2 Isokinetic, single leg and bilateral countermovement jump (CMJ) results of each group

Test	Group 1 Pre-Injury (n=20)		Group 2: Healthy Controls (n=35)	Pre-injury vs controls effect size (95%CI)	Pre-injury vs controls *P* value
	Involved limb	Uninvolved limb	Dominant Limb		
Quad PT Rel ($N.m.kg^{-1}$)	3.2±0.37	3.13±0.44	3.06±0.4	0.35 (-0.21 to 0.92)	0.200
HS PT Rel ($N.m.kg^{-1}$)	1.75±0.26	1.79±0.3	1.68±0.22	0.29 (-0.27 to 0.86)	0.335
SLCMJ Jump Height (cm)	18.5±4.4	19.2.2±3.4	18.8±2.3	-0.09 (-0.65 to 0.47)	0.787
SLCMJ RSI Mod	0.22±0.08	0.24±0.07	0.24±0.05	-0.25 (-0.82 to 0.31)	0.510
SLCMJ Peak Power Rel (W/Kg)	31.7±4.3	32.7±4.4	31.9±4.2	-0.05 (-0.61 to 0.52)	0.855
CMJ Jump Height (cm)	36.4±7.4		37.5±3.6	-0.22 (-0.78 to 0.35)	0.231
CMJ RSI Mod	0.46±0.11		0.49±0.07	-0.30 (-0.86 to 0.27)	0.354
CMJ Peak Power Rel (W/Kg)	52.1±6.3		52.8±4.9	-0.13 (-0.69 to 0.44)	0.695

Normalised quadriceps and hamstring peak torque were higher in the uninvolved limb of the ACL group prior to RTS compared to those who were uninjured ($g = 0.77$, 95%CI [0.19, 1.36]; $p = 0.018$, and $g = 0.77$, 95%CI [0.19, 1.35]; $p = 0.005$ respectively). There were no significant differences in SLCMJ height, RSImod and relative peak power between the uninvolved limb of the ACL group and uninjured controls (Table 6.3).

Normalised hamstring peak torque was significantly higher in the reconstructed limb of the ACL group following rehabilitation compared to uninjured controls ($g = 1.32$, 95%CI [0.70, 1.93]; $p \leq 0.0001$), whereas there were no significant between-group differences in normalised quadriceps peak torque (Table 6.4).

There were large significant differences between the ACL group following surgery and uninjured controls in SLCMJ height ($g = -1.64$, 95%CI [-2.28, -0.99]; $p \leq 0.0001$), RSImod ($g = -0.93$, 95%CI [-1.52, -0.34]; $p = 0.004$), and jump height symmetry ($g = -1.51$, 95%CI [-2.14, -0.87]; $p \leq 0.001$) (Table 6.4).

There were large significant differences between the ACL group following surgery and uninjured controls in CMJ height ($g = -1.17$, 95%CI [-1.77, -0.56]; $p \leq 0.0001$) and RSImod ($g = -0.89$, 95%CI [-1.48, -0.30]; $p = 0.001$). Moderate differences in relative peak power ($g = -0.76$, 95%CI [-1.34, -0.18]; $p = 0.008$) were also present between groups (Table 6.5).

Table 6.3 Isokinetic and single leg countermovement jump (SLCMJ) results of the uninvolved limb of the injured group and healthy matched controls

Test	Group 1 Pre-Injury (n=20)	Group 1 Post-Injury (n=20)	PRE vs POST effect size (95%CI)	PRE vs POST P value	Pre-Post Percentage difference (95%CI)	Group 2: Healthy Controls (n=35)	Post-injury vs controls effect size (95%CI)	Post-injury vs controls *P* value
	Uninvolved limb	Uninvolved limb						
Quad PT Rel (N.m.kg^{-1})	3.13±0.44	3.39±0.45	-0.57 (-1.23 to 0.08)	0.021	9.34% (6.45 to 12.23)	3.06±0.4	0.77 (0.19 to 1.36)	**0.018**
HS PT Rel (N.m.kg^{-1})	1.79±0.3	1.87±0.29	-0.27 (-0.91 to 0.38)	0.261	7.36% (5.08 to 9.64)	1.68±0.22	0.77 (0.19 to 1.35)	**0.005**
SLCMJ Jump Height (cm)	19.2.2±3.4	18.6±3.3	0.18 (-0.47 to 0.82)	0.517	-1.03% (-1.35 to -0.71)	18.8±2.3	-0.08 (-0.64 to 0.48)	0.568
SLCMJ RSI Mod	0.24±0.07	0.24±0.06	-0.03 (-0.67 to 0.61)	0.900	10.7% (7.38 to 14.02)	0.24±0.05	0.10 (-0.46 to 0.66)	0.987
SLCMJ Peak Power Rel (W/Kg)	32.7±4.4	33.0±3.9	0.17 (-0.47 to 0.82)	0.232	6.01% (4.15 to 7.87)	31.9±4.2	0.25 (-0.31 to 0.82)	0.385

PT (peak torque), Rel (relative to body mass), N (Newtons), m (meters), kg (kilograms), W (Watts), cm (centimeters)

Table 6.4 Isokinetic and single leg countermovement jump (SLCMJ) results of the involved limb of the injured group and healthy matched controls

Test	Group 1 Pre-Injury (n=20)	Group 1 Post-Injury (n=20)	PRE vs POST effect size (95%CI)	PRE vs POST P value	Pre-Post Percentage difference (95%CI)	Group 2: Healthy Controls (n=35)	Post-injury vs controls effect size (95%CI)	Post-injury vs controls *P* value
	Involved limb	Involved limb						
Quad PT Rel ($N.m.kg^{-1}$)	3.2±0.37	2.98±0.51	0.48 (-0.17 to 1.13)	0.036	-7% (-9.2 to -4.8)	3.06±0.4	-0.18 (-0.74 to 0.39)	0.993
HS PT Rel ($N.m.kg^{-1}$)	1.75±0.26	1.96±0.19	-0.90 (-1.58 to -0.23)	**≤0.0001**	14.2% (9.8 to 18.6)	1.68±0.22	1.32 (0.70 to 1.93)	**≤0.0001**
SLCMJ Jump Height (cm)	18.5±4.4	14.6±2.9	1.03 (0.34 to 1.71)	**0.005**	-12.08% (-16.54 to -9.06)	18.8±2.3	-1.64 (-2.28 to -0.99)	**≤0.0001**
SLCMJ RSI Mod	0.22±0.08	0.18±0.06	0.50 (-0.16 to 1.15)	0.099	-5.04% (-6.6 to -3.48)	0.24±0.05	-0.93 (-1.52 to -0.34)	**0.004**
SLCMJ Peak Power Rel (W/Kg)	31.7±4.3	30.2±7	0.25 (-0.39 to 0.90)	0.411	-3.14% (-3.61 to -2.67)	31.9±4.2	-0.31 (-0.88 to 0.25)	.325

PT (peak torque), Rel (relative to body mass), N (Newtons), m (meters), kg (kilograms), W (Watts), cm (centimeters)

Table 6.5 Countermovement Jump test results of each group

Test	Group 1 Pre-Injury (n=20)	Group 1 Post-Injury (n=20)	PRE vs POST effect size (95%CI)	PRE vs POST P value	Pre-Post Percentage difference (95%CI)	Group 2: Healthy Controls (n=35)	Post-injury vs controls effect size (95%CI)	Post-injury vs controls *P* value
CMJ Jump Height (cm)	36.4±7.4	33.2±3.7	0.54 (-0.12 to 1.19)	0.042	-5.92% (-7.76 to -4.08)	37.5±3.6	-1.17 (-1.77 to -0.56)	**≤0.0001**
CMJ RSI Mod	0.46±0.11	0.42±0.09	0.39 (-0.26 to 1.04)	0.083	-5.51% (-7.22 to -3.8)	0.49±0.07	-0.89 (-1.48 to -0.30)	**0.001**
CMJ Peak Power Rel (W/Kg)	52.1±6.3	49.1±4.6	0.53 (-0.12 to 1.19)	0.042	-4.94% (-6.47 to -3.41)	52.8±4.9	-0.76 (-1.34 to -0.18)	**0.008**

W (Watts), cm (centimeters), kg (kilograms)

6.2.2 Part 2: the effect of ACL reconstruction on the uninjured limb

Uninvolved limb pre-injury and post ACLR performance for each of the participants is shown in figures 6.2b, 6.3b and 6.4b). There was no significant main effect of time ($F(1,19) = 0.43$, $p = 0.838$), but there was a significant main effect of injury on normalised quadriceps peak torque ($F(1,19) = 7.996$, $p = 0.011$). A significant interaction effect between time and injury was present ($F(1,19) = 32.8$, $p \leq 0.001$), showing an increase in normalised quadriceps peak torque in the uninvolved limb. No main effect of injury was observed for normalised hamstring peak torque ($F(1,19) = 0.47$, $p = 0.5$) and no significant interaction effect between time and injury ($F(1,19) = 3.8$, $p = 0.065$). There was only a significant main effect of time on normalised hamstring peak torque ($F(1,19)= 7.35$, $p = 0.014$), which showed improvements in normalised hamstring peak torque in the uninvolved limb attributable to the passage of time only following surgery. There were no significant main or interaction effects of time and/or injury on SLCMJ jump height, relative peak power and RSI Mod in the uninvolved limb.

Moderate effect size differences in normalised quadriceps peak torque were observed post ACL reconstruction in comparison to pre-injury values ($g = 0.57$, 95%CI [-0.08, 1.23]; $p \leq 0.021$), whereas there were no significant differences in normalised hamstring peak torque (Table 6.3).

6.2.3 Part 3: the effect of ACL reconstruction on the injured limb

Involved limb pre-injury and post ACLR performance for each of the participants is shown in figures 6.2a, 6.3a and 6.4a. There was no significant main effect of time ($F(1,19) = 0.43$, $p = 0.838$), but there was a significant main effect of injury on normalised quadriceps peak torque ($F(1,19) = 7.996$, $p = 0.011$). A significant interaction effect between time and injury was present ($F(1,19) = 32.8$, $p \leq 0.001$), showing deterioration in normalised quadriceps peak torque in the ACL reconstructed limb. No main effect of injury was observed for normalised hamstring peak torque ($F(1,19) = 0.47$, $p = 0.5$) and there was no significant interaction effect between time and injury ($F(1,19) = 3.8$, $p = 0.065$). A significant main effect of time on normalised hamstring peak torque ($F(1,19)= 7.35$, $p = 0.014$) was shown, which indicates improvements in normalised hamstring peak torque in the ACL reconstructed limb following surgery.

There was a significant main effect of time ($F(1,19)= 5.28$, p = 0.033) and injury ($F(1,19) = 49.56$, p $\leq$ 0.001) on SLCMJ height, relative peak power ($F(1,19) = 31.75$, p $\leq$ 0.001), and

RSImod ($F(1,19) = 45.42$, $p \leq 0.001$) in the ACL reconstructed limb. A significant interaction effect was present between time and injury in jump height ($F(1,19) = 11.53$, $p = 0.003$), relative peak power ($F(1,19) = 5.86$, $p = 0.026$), and RSImod ($F(1,19) = 8.02$, $p = 0.011$), indicating SLCMJ performance had not returned to baseline. Conversely, normalised hamstring peak torque was significantly higher following ACL reconstruction compared to pre-injury values ($g = 0.90$, 95%CI [0.23, 1.58]; $p \leq 0.0001$). No significant differences in normalised quadriceps peak torque were present (Table 6.4).

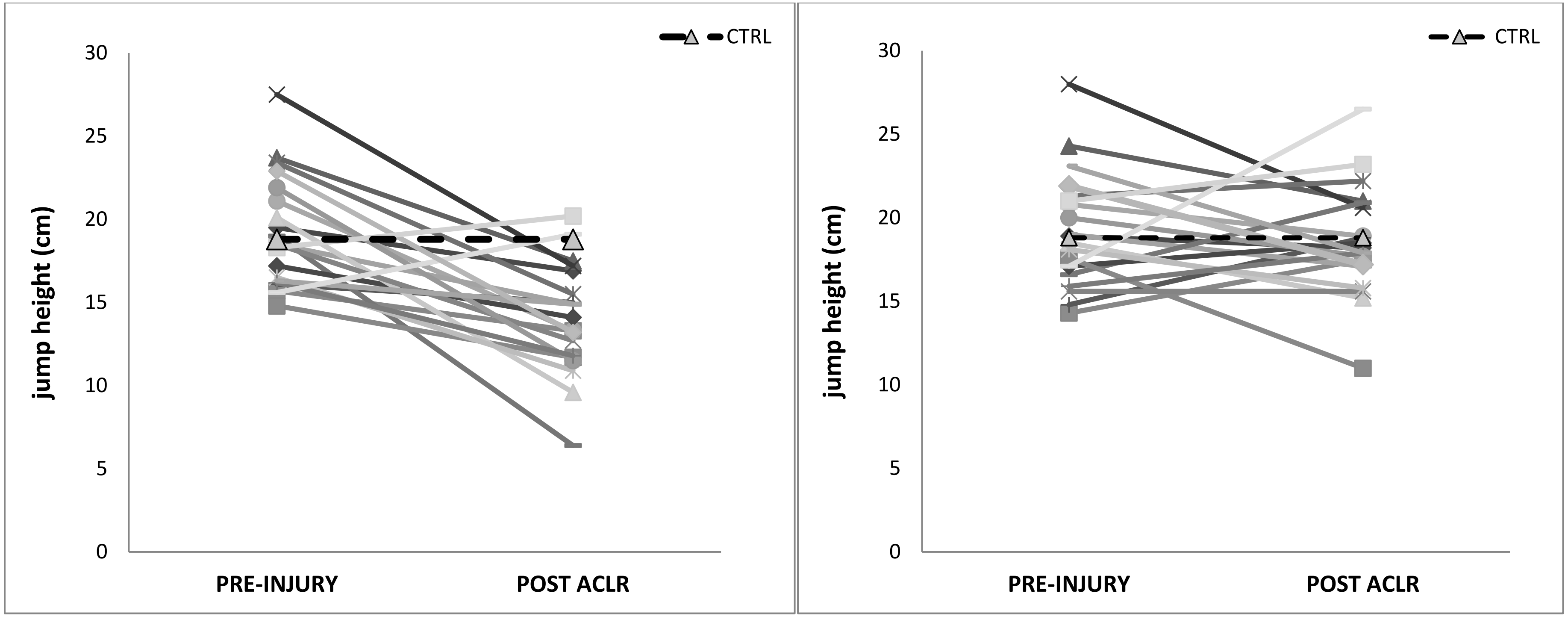


Figure 6.2a Involved limb and **Figure 6.2b** uninvolved limb single leg countermovement jump (SLCMJ) height pre-injury and post anterior cruciate ligament reconstruction (ACLR). Centimeters (cm). Control group (CTRL)

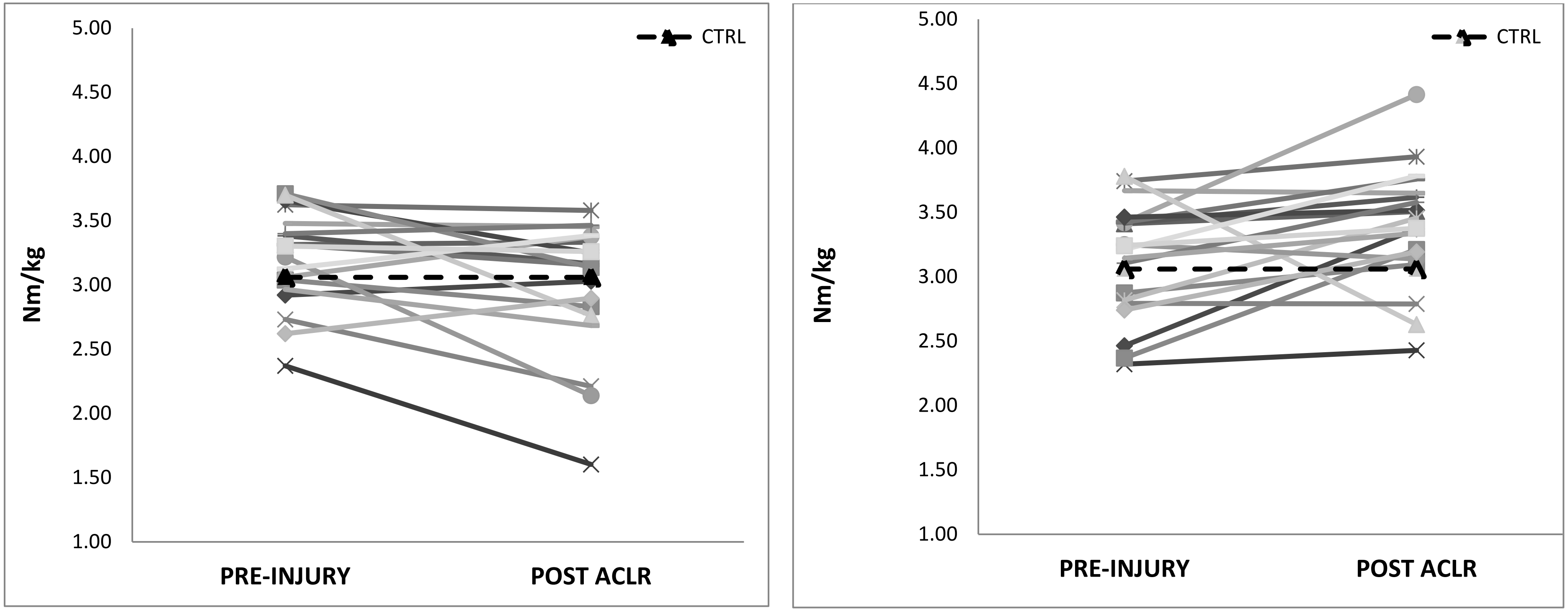
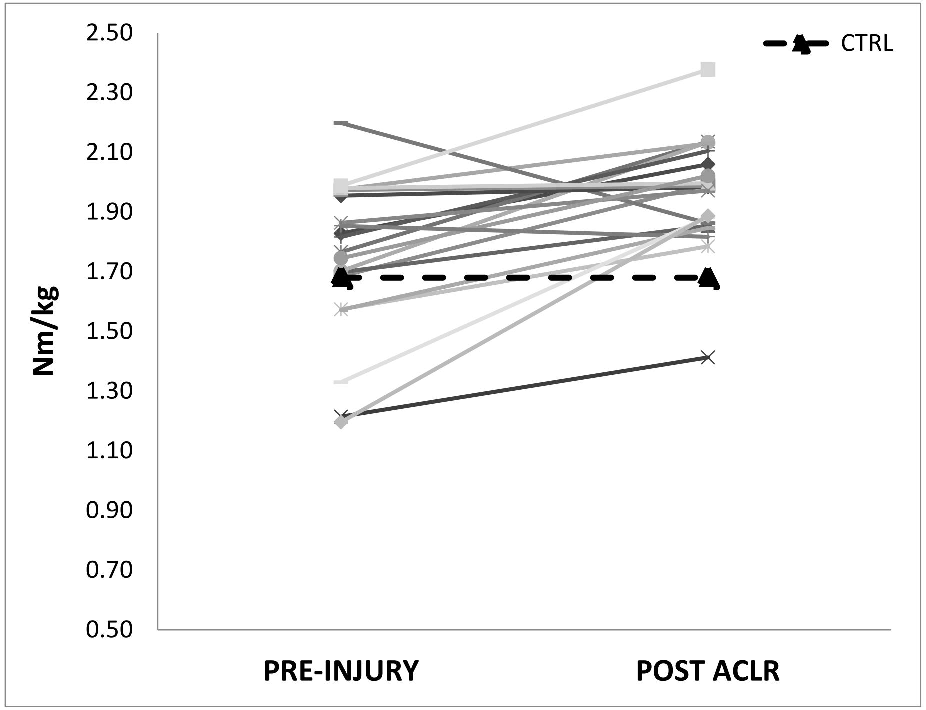


Figure 6.3a Involved limb and **Figure 6.3b** uninvolved limb knee extension strength pre-injury and post anterior cruciate ligament reconstruction (ACLR). Newton (N). Meter (m). Kilogram (kg). Control group (CTRL)



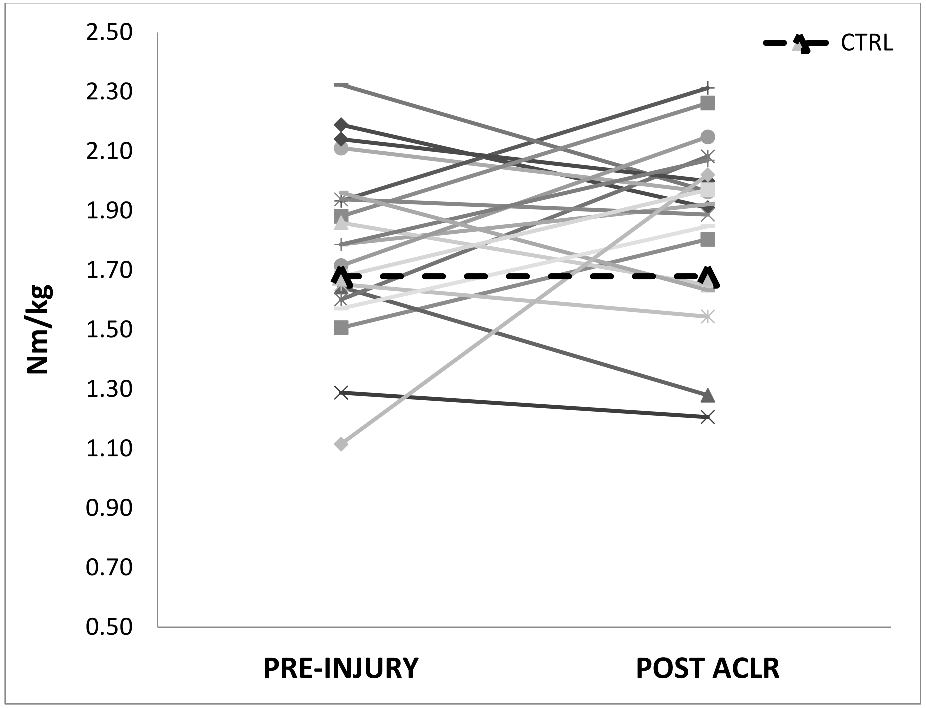


Figure 6.4a Involved limb and **Figure 6.4b** uninvolved limb knee flexion strength pre-injury and post anterior cruciate ligament reconstruction (ACLR). Newton (N). Meter (m). Kilogram (kg). Control group (CTRL)

6.2.4 Part 4: the effect of ACL reconstruction on CMJ performance

Pre-injury and post ACLR CMJ height for each of the participants is shown in figure 6.5. No significant reductions in CMJ RSImod were present between the ACL reconstructed group before ACL rupture and after reconstruction at the time of RTS. Although not achieving our determined alpha level, moderate differences in CMJ jump height (g = 0.54, 95%CI [-0.12, 1.19]; p = 0.042) and relative peak power (g = 0.53, 95%CI [-0.12, 1.19]; p = 0.042) were present between the ACL reconstructed group before injury and after reconstruction at the end of rehabilitation around at the time of RTS (Table 6.5).

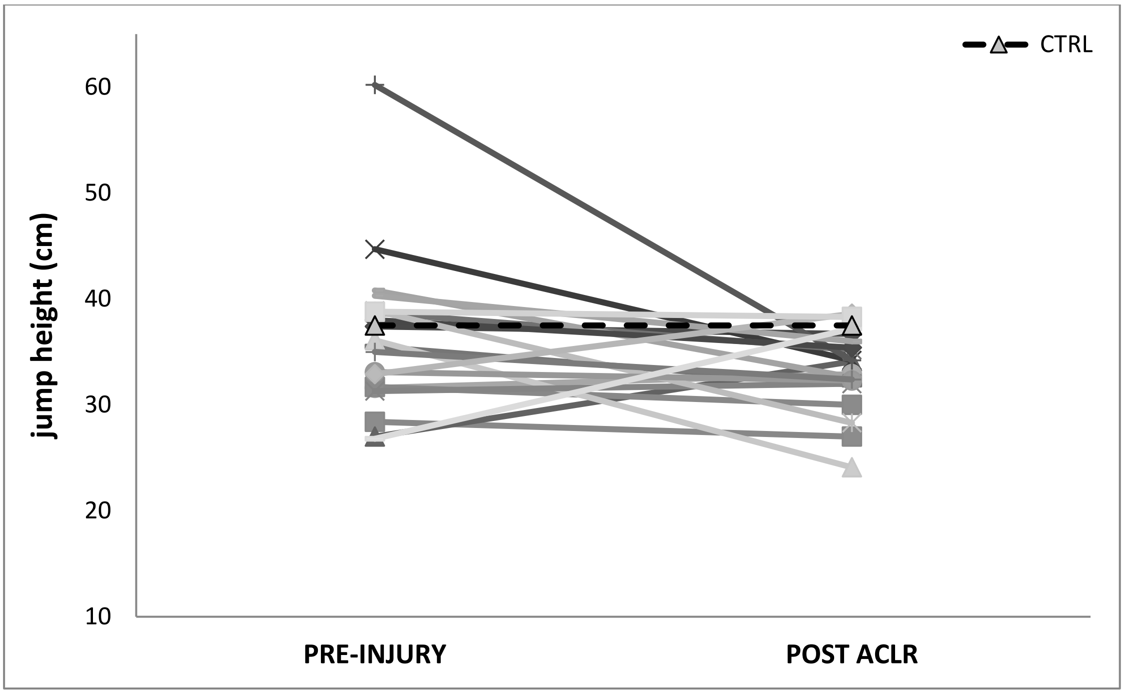


Figure 6.5 Countermovement jump (CMJ) height pre-injury and post anterior cruciate ligament reconstruction (ACLR). Centimeters (cm). Control group (CTRL)

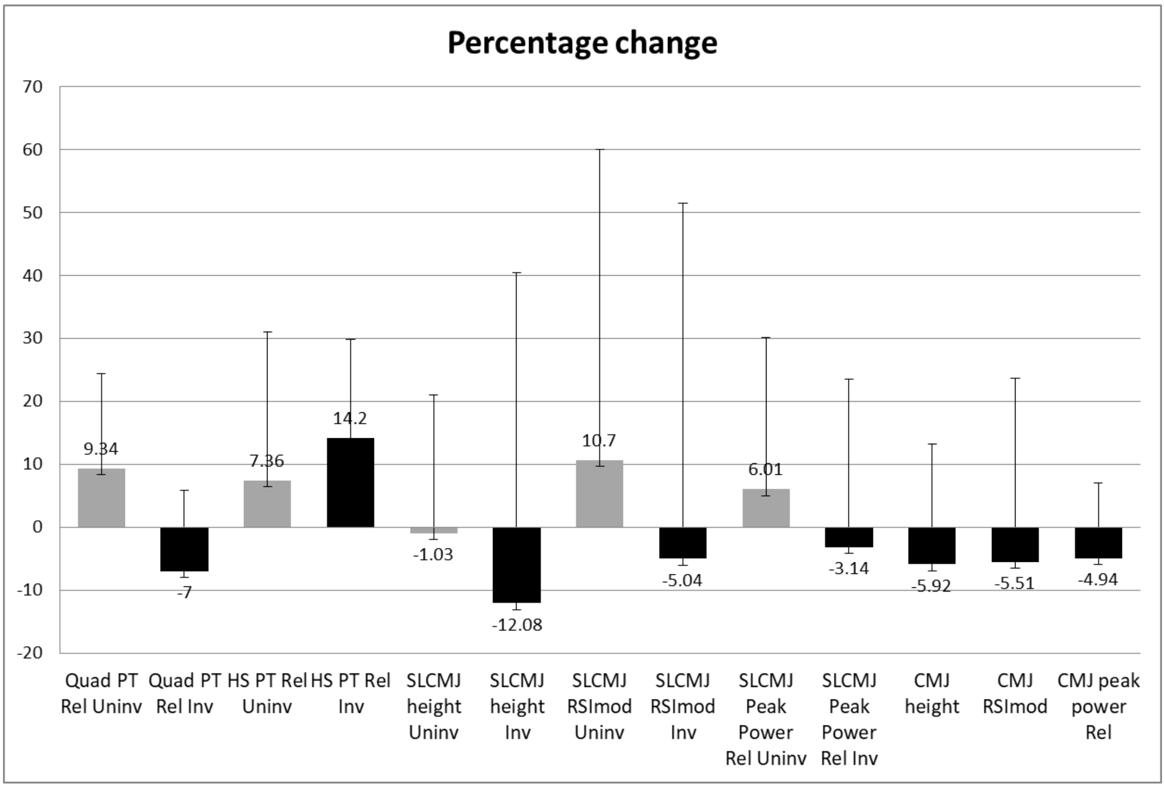


Figure 6.6 Percentage changes from pre-injury to post anterior cruciate ligament reconstruction of all variables analysed. Quadriceps relative peak torque (Quad PT Rel), Hamstrings relative peak torque (HS PT Rel), single leg countermovement jump (SLCMJ), reactive strength index modified (RSImod), relative peak power (peak power Rel), countermovement jump (CMJ), uninvolved (Uninv), involved (Inv)

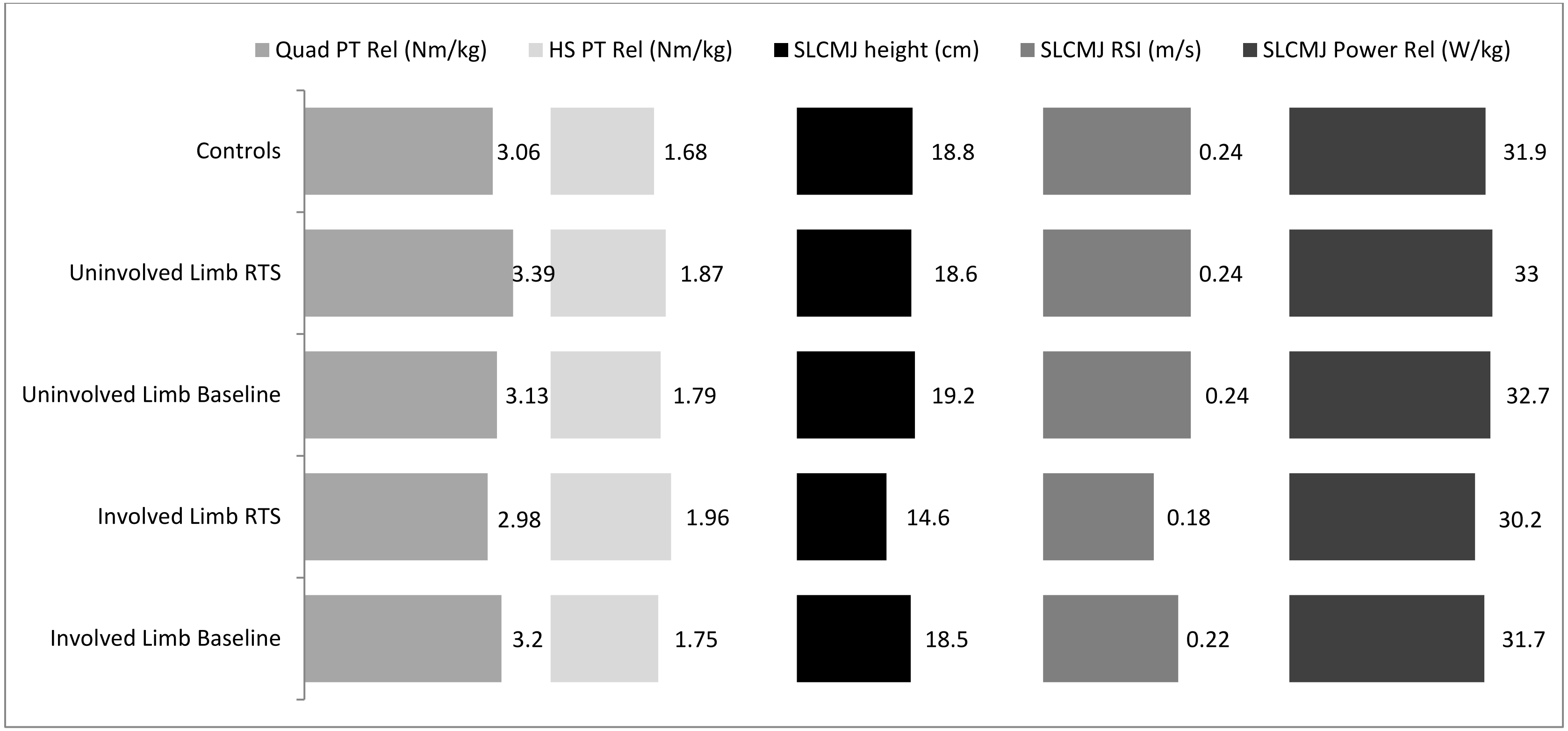


Figure 6.7 Knee extension and flexion strength, single leg countermovement jump height, RSI and relative peak power. Newton (N). Meter (m). Centimetre (cm). Metre (m). Second (s). Kilogram (kg). Watt (W). RTS (return to sport)

6.3 Discussion

Our aim was to examine how pre-injury data can be used to guide performance recovery and inform physical readiness as part of RTS decision making. Cumulatively, the results indicate that residual deficits in strength and power are present following ACL reconstruction (7.6 ± 1.8 months post-surgery) and the pattern of recovery is diverse across tests and metrics selected. Use of both the uninvolved limb and normative data of matched controls as a proxy measure to determine the level of performance recovery may not always be appropriate to estimate the degree of recovery and practitioners are encouraged to collect routine pre-injury data where possible to assess physical readiness most accurately to RTS.

6.3.1 Recovery of involved limb and bilateral performance

Deficits in knee extension peak torque relative to controls have been documented in male multidirectional team sport athletes more than 6 months following surgery (Maestroni, Read, 2021b). In our study, group mean values indicated normalised quadriceps strength levels in the ACL cohort at the time of RTS were in line with recommended thresholds (> 3.0 Nm/kg at 60°/s) (Welling, Benjaminse, 2019), and did not significantly differ from the uninjured group indicating this should be the first rehabilitation target. However, there was some variability across participants (figure 6.3a), and normalised quadriceps strength of the involved limb post ACL reconstruction showed reduced values compared to those recorded pre-injury (g = - 0.48, p = 0.036), suggesting that comparison with pre-injury values may add important information regarding strength recovery following ACL reconstruction. Our professional athletes completed a progressive strength training intervention during rehabilitation which has been shown to attenuate strength deficits following ACL rehabilitation (Welling, Benjaminse, 2019). However, normalised quadriceps strength on the involved limb was reduced compared to baseline values and substantially lower than the contralateral limb at the end of rehabilitation. These data indicate that both individual limb torque scores need to be considered in RTS decision making, and when pre-injury data are available, assessment of symmetry may be secondary compared to attainment of the athletes own benchmark scores on each limb. Longer rehabilitation periods (≥ 9 months) may also be needed to recover knee extensor torque deficits (Bodkin et al. , 2020). Optimal knee extension strength recovery is associated with reduced risk of future knee injury (Grindem, Snyder-Mackler, 2016) and osteoarthritis (Culvenor et al. , 2018), greater subjective knee functional scores (IKDC) (Chaput et al. , 2021), articular cartilage status (Everhart et al. , 2020), and reduced inter-limb and intralimb maladaptive compensation strategies during unilateral and bilateral jumping and landing tasks (Maestroni, Papadopoulos, 2021a). Targeted interventions with a maximal strength emphasis should be integral components of rehabilitation until at the very least normative values (>3.0 Nm/Kg) are met.

Our study revealed a reduction in CMJ height, RSImod and relative peak power in ACL reconstructed players in comparison to baseline pre-injury performance (CMJ height g = - 0.54, p = 0.042; RSImod g = - 0.39, p = 0.083; relative peak power g = - 0.53, p = 0.042) and healthy controls (CMJ height g = -1.17, $p \leq 0.0001$; RSImod g = - 0.89, p = 0.001; relative peak power g = - 0.76, p = 0.008). For some individuals, CMJ height was substantially lower than their pre-injury baseline (Figure 6.5). Other researchers have suggested that recovery of CMJ height is still incomplete at the time to RTS in comparison to healthy controls (Read, Michael Auliffe, 2020b). There was also evidence of large reductions in SLCMJ height (g = -1.64, $p \leq 0.0001$) and RSImod (g = -0.93, p = 0.004) on the involved limb, and this trend was consistent across most participants (Figure 6.2a). To execute a single leg jump, there is a higher relative force requirement compared to bilateral (estimated ~ 1.62 times of those in a CMJ) to displace body mass vertically, resulting in slower movement velocities(Cohen D, 2020). We observed a greater reduction in SLCMJ (-12.08%, than CMJ height (-5.92%) following ACL reconstruction (figure 6.6). Therefore, as the deficits in SLCMJ height were twice the magnitude of those in the CMJ, it could be suggested that SLCMJ height offers a better reflection of limb capacity compared to measurement of the same variable in a bilateral jump. The CMJ task allows athletes to re-distribute their impulse production via inter-limb compensations in an attempt to maintain similar jump heights (Read, Michael Auliffe, 2020b). These data can be derived from dual force platforms, but such technology is not commonly available to clinicians. Measurement of SLCMJ height is obtainable using a variety of measurement tools and may be a useful indicator to determine the recovery of limb capacity around the time of RTS.

Previous research has reported SLCMJ normative scores of > 17 cm in multidirectional field sport athletes at the late stages of rehabilitation (O'Malley, Richter, 2018). These values are in line with the results of our study (figure 6.7) which included healthy professional soccer players. Therefore, ~ 18 cm may represent a realistic target to achieve by the end of rehabilitation for field sport athletes if pre-injury values are not available. However, as many athletes baseline scores were higher (figure 6.2a), this further highlights the importance of routine pre-injury data collection at regular intervals to ensure the most accurate benchmark is established. In addition, the ACL reconstructed limb showed reduced RSImod in comparison to the dominant limb of healthy controls (figure 6.7). Decreased stretch shortening cycle performance has been recently documented in similar cohorts (King, Richter, 2018b, Lloyd, Oliver, 2020, Read, Davies, 2020a) and is associated with higher risk of ipsilateral and contralateral ACL injury (King, Richter, 2021a, b), as well as reduced sports performance (Li, Newton, 2019, Maloney, Richards, 2017). Thus, increased emphasis on reconditioning strategies to recover ballistic performance needs to be embedded in the RTS pathway together with progressive strength training interventions (Buckthorpe, 2019, Buckthorpe and Roi, 2017).

6.3.2 The use of proxy measures in decision making

When making RTS decisions, comparison with preinjury is often impracticable. Our data suggest that in single leg jumping tasks, healthy matched controls including mean values for teammates or published data for a similar playing level could provide a suitable reference of the minimum target which should be achieved in monitoring the recovery of physical performance following ACL reconstruction. However, utilisation of strength scores in healthy controls may not follow the same pattern. Overestimation of functional improvements during rehabilitation have been reported previously when using pre-operative scores on the contralateral limb as a reference value at the time of RTS owing to a bilateral reduction in physical performance following ACL reconstruction (Wellsandt, Failla, 2017a) inflating limb symmetry indexes. In contrast, we observed that normalised quadriceps and hamstring strength improved from pre-injury following the completion of rehabilitation on the uninvolved limb in the ACL reconstructed group and scores were greater than matched controls (figure 6.7) suggesting an underestimation in the degree of recovery if the latter comparison was used. Conversely, involved limb reductions in quadriceps strength at the time of RTS were greater when compared to pre-injury data (7%) and healthy controls (2.6%) suggesting use of healthy control values would overestimate the degree of recovery for involved limb quadriceps strength. If the contralateral limb was used post injury, a larger between-limb difference was present (14%) and this would underestimate the degree of recovery. Our participants were full-time athletes attending rehabilitation 5 days per week, of which, knee extension and flexion strength were considered a priority. This suggests that when a comprehensive rehabilitation programme including progressive strength training is followed, comparison with matched controls alone is not enough, although it does represent the first achievable milestone to ensure strength recovery. However, it should be considered that training age and routine exposure to strength and conditioning of the healthy controls were not examined. Similarly, use of the contralateral limb may be misleading and can underestimate recovery when significant training adaptations have occurred. Thus, proxy measures to determine the level of performance recovery may not always be appropriate.

Large performance reductions were observed in bilateral CMJ height and RSImod based on healthy controls values, but the corresponding deficits based on true benchmark values were classified as moderate, suggesting a potential underestimation of recovery of these metrics when using healthy control data. SLCMJ performance on the uninvolved limb showed no significant difference pre-injury vs. RTS although there was a slight reduction in jump height. Our data indicate that both healthy controls and the unaffected limb could be used as a reference in monitoring SLCMJ performance recovery (i.e., achievement of pre-injury baseline values) on a group level, but caution should be applied as several athletes pre-injury SLCMJ scores were greater than these values.

Our data also suggests that a comprehensive rehabilitation program can mitigate reductions in contralateral knee strength and power secondary to surgery and reduced load exposure. Maintaining or even increasing quadriceps and plyometric qualities can have important implications in reducing subsequent ACL injury risk to the uninjured limb in male athletes following ACL reconstruction (King, Richter, 2021b), and thus should be monitored during rehabilitation. Further research is encouraged to measure temporal recovery across multiple time-points in these physical qualities to determine the trajectory of recovery more accurately.

Changes from baseline pre-injury scores following ACL reconstruction should be interpreted relative to the measurement error in the metrics used (Table 6.1). CMJ height and relative peak power displayed CV values of 2.7 and 2.1% respectively. The corresponding % changes following ACL reconstruction and rehabilitation were 5.92 and 4.94% indicating a ‘real’ change had occurred with differences larger than the observed measurement error. RSImod reduced by 5.51% but the CV value was 8.6% which suggests the observed differences were within the error range and could be considered less meaningful. Similarly, only SLCMJ height showed changes following ACL reconstruction larger than the measurement error (-12% reduction; CV: 5.2%), whereas RSImod and relative peak power had a greater CV% relative to the observed % change. In addition, we were not able to collect follow up data on the uninjured controls to determine what is ‘normal’ seasonal variation in these metrics.

Our sample size precluded us from conducting analysis based on graft type and this may have an effect on strength and power qualities. The majority of our players had a bone-patellar tendon-bone graft, which can explain the incomplete and delayed recovery of knee extensor and concentric jump outputs deficits, in comparison to similar cohorts with a semitendinosus/gracilis graft type (Miles and King, 2019). Future research may wish to examine temporal recovery of physical qualities using benchmark pre-injury data considering different graft types. Finally, none of the assessments directly assessed eccentric qualities, which may show divergent recovery patterns and deficits, and therefore our conclusions should be principally related to concentric strength / jump outputs that ultimately reflect capacity to generate concentric impulse. Our data were limited to adult male professional football players. Therefore, generalisation of these results to pediatric, adolescent and female athletes requires caution. Although the involved surgeons and rehabilitation specialists belonged to the same Orthopaedic and Sports Medicine Hospital, potential variations in surgical techniques and rehabilitation strategies could have been present and should also be acknowledged.

6.4 Conclusion

The current study indicates that ACL reconstruction has a detrimental effect on strength and power characteristics in professional soccer players, but the pattern was diverse. Peak knee extension strength, CMJ and SLCMJ height, RSImod, and relative peak power values at the end of rehabilitation prior to RTS remained below those recorded pre-injury. Furthermore, in spite of the fact that players approached strength values deemed sufficient in the ACL reconstructed limb and exceeded these criteria in the contralateral limb, large differences in SLCMJ height and RSImod were still evident on the ACL reconstructed limb in comparison to uninjured matched controls. These differences were smaller when assessed bilaterally (i.e., CMJ test), indicating that SLCMJ can be used to more closely evaluate the recovery of individual limb physical capacity. These data can be easily obtained using a variety of cost-effective methods, especially compared to isokinetic assessments which require expensive equipment and are time in-efficient.

Our findings are summarised in table 6.6, and have clinical implications and can be used to help guide the RTS process. Cumulatively, we suggest that an optimal approach to determine physical recovery at the time of RTS would include the following: 1) data collected as early as possible (baseline pre-injury if available or if not pre-operative values on the uninvolved limb) to inform readiness to RTS as this should be considered the gold standard reducing the need for proxy measures of limb recovery, which can overestimate or underestimate limb function; 2) consider both absolute scores on each limb and not just symmetry values; 3) in situations where baseline pre-injury data are not available, compare to uninjured matched controls to ensure minimum standards are met. In addition, we suggest including both unilateral and bilateral assessments with a range of demands across the strength, power and velocity spectrum to ensure performance is measured under different task constraints.

Table 6.6 Summary table

Research question	Significant findings
Do the strength and power characteristics differ in soccer players who sustained an ACL injury and underwent subsequent reconstructive surgery to those of uninjured players?	No difference between groups in strength, power, and reactive strength characteristics at baseline assessment, but lower performance was indicated in ACL reconstructed players at the end of rehabilitation
How does ACL reconstruction effect isokinetic knee extension / flexion strength and SLCMJ performance on the ***un-involved limb***?	Increase in quadriceps and hamstring strength from pre-injury to RTS. No significant differences from pre-injury in SLCMJ height, power and reactive strength following ACL reconstruction
How does ACL reconstruction effect isokinetic knee extension / flexion strength and SLCMJ performance on the ***involved limb***?	Increase in hamstring strength from pre-injury to RTS Decrease in quadriceps strength, SLCMJ height and reactive strength following ACL reconstruction
How does ACL reconstruction effect ***CMJ performance***?	Decrease in jump height, reactive strength and power following ACL reconstruction

After having examined the recovery patterns in strength and power characteristics from pre-injury to the later stages of rehabilitation, we then explored how strength and reactive strength levels could affect stretch-shortening cycle biomechanics following ACL reconstruction

CHAPTER 7: Empirical STUDY 2

Single leg drop jump is affected by physical capacities in male soccer players following ACL reconstruction

In this chapter we examined biomechanical differences between the ACL reconstructed and uninvolved limb during a SLD. In addition, we explored how strength and reactive strength levels affected SLD biomechanical variables. This study was published in Science and Medicine in Football Journal

Maestroni, L., Turner, A., Papadopoulos, K., Pedley, J., Sideris, V., & Read, P. (2023). Single leg drop jump is affected by physical capacities in male soccer players following ACL reconstruction. Science and Medicine in Football Journal

7.0 Introduction

Residual deficits in strength and power qualities have been identified in multidirectional field sport athletes in the later stages of rehabilitation and at the point of return to sport (RTS) following anterior cruciate ligament (ACL) reconstruction (King, Richter, 2021b, King, Richter, 2018b, Lloyd, Oliver, 2020, Maestroni, Read, 2021b, Read, Davies, 2020a, Read, Michael Auliffe, 2020b). The ability to rapidly transition from eccentric to concentric muscle actions, is commonly assessed using the reactive strength index (RSI) in rebound tasks (Flanagan and Comyns, 2008). RSI has been used to determine plyometric capabilities in athletic cohorts after ACL reconstruction, with significant between-limb and group (compared with healthy controls) differences (King, Richter, 2018b, Kotsifaki et al. , 2022, Lloyd, Oliver, 2020, Read, Davies, 2020a, Read et al. , 2022a), and associations with increased risk of ipsilateral re-injury and contralateral ACL injury (King, Richter, 2021a, b). Recent findings (Read, Pedley, 2022a) also showed that, from mid to late stage rehabilitation, a trend was evident of improved single-leg drop jump (SLDJ) performance (RSI) and ground reaction force characteristics. However, RSI was the only variable to change significantly on the involved limb across the 2 time points. Therefore, changes in RSI, may not be reflective of alterations in ground reaction force characteristics (Read, Pedley, 2022a), and are unaffected by whether individuals possess spring-like characteristics (Pedley et al. , 2020). Maladaptive functioning of the above dampening mechanisms have been demonstrated following ACL reconstruction (Read, Pedley, 2022a). This can impair force attenuation in the short timeframes required, exposing athletes to large impact forces during fast sporting actions such as jumping, landing, and change of direction, which are commonly associated with high peak ACL strain (Dos'Santos et al. , 2019, Fox, 2018).

Recent evidence has examined performance and kinetic variables during the SLDJ in athletic cohorts following ACL reconstruction (Birchmeier, Lisee, 2019, Crotty et al. , 2022, King, Richter, 2018b, Read, Pedley, 2022a). Less data is available to describe SLDJ kinematics. Current findings (King, Richter, 2018b, Kotsifaki, Van Rossom, 2022) indicate that during the stance and propulsion phase, the ACL reconstructed limb displays greater hip and trunk flexion angles, but reduced knee flexion angles in comparison to the uninvolved limb. These studies used three-dimensional motion capture, which is considered the gold standard for assessing athletes' movement quality but is expensive, requires technical expertise, and large periods of time for data collection. Wearable technology has been recently proposed as a more clinically viable alternative (Marques et al. , 2022). Sensors can easily be attached to specific anatomical locations, and preliminary data suggests they can be used to identify between-limb kinetic and kinematic differences following ACL reconstruction (Marques, Auliffe, 2022). There is an absence of research to examine movement tasks associated with prospective injury risk measured using wearable technology, and no data in adult male multidirectional field sports athletes.

To enhance our knowledge of factors that underpin performance and movement strategy used during RTS tests, a clear understanding of the influence of physical capacities on SLDJ mechanics is warranted. A recent study including male multidirectional field sports athletes at the time of RTS following ACL reconstruction indicated that knee extension strength explained a third of the variance in SLDJ RSI (R^2 = 33%, $p < 0.001$) (Crotty, Daniels, 2022). However, ground reaction force and kinematic variables were not examined. Birchmeier et al. (Birchmeier, Lisee, 2019) reported that RSI measured during a SLDJ, peak knee extension torque, and rate of torque development explained two thirds of the variance in triple hop distance (R^2 = 61.8%, $p < 0.001$) in male and female athletes. SLDJ ground reaction force characteristics and kinematics were not measured, no associations between knee extension strength and SLDJ mechanics were examined, and the relationship between RSI and performance was assessed in the triple hop only. Considering that quadriceps strength plays a key role in attenuating force during the deceleration phase of ground contact (He et al. , 2022, Ward, Blackburn, 2018), more data are required to examine if there are differences in SLDJ kinetics and kinematics depending on a soccer players level of physical capacity including knee extension strength and RSI .

This study aimed to 1) investigate performance, kinetic and kinematic differences between the ACL reconstructed and the uninvolved limbs using practically viable methods which do not require a biomechanics laboratory enhancing utility in the field; and 2) examine if there are differences in SLDJ performance and mechanics in soccer players with heightened isokinetic knee extension and reactive strength.

7.1 Methods

7.1.1 Participants

Sixty-four male soccer players participating in the Qatar Stars and Qatar Gas Leagues (22.6 ± 3.7 years; 174 ± 7.0 cm; 70 ± 10.2 kg) at an average of 8.3 (± 1.9) months post ACL reconstruction (bone-patella-tendon bone (78%), with the remaining players (22%) all semitendinosus and gracilis hamstring tendon grafts), volunteered to take part in this study. Players competing at a registered club in Qatar are provided the opportunity to undergo surgery and rehabilitation at the specialist Orthopaedic and Sports Medicine centre which was the designated research site for the study. Inclusion criteria required players to have no history of previous ACL injury / surgery, or other knee ligament or cartilage injury / surgery of either the operated or non-operated leg. Players were excluded if they reported previous ACL injury/surgery or other knee ligament or cartilage injury/surgery of the operated or non-operated leg.

All participants were involved in an intensive rehabilitation programme (5 days per week) (Kyritsis, Bahr, 2016), at the same Orthopedic and Sports Medicine Hospital by a specialist team of sports physiotherapists who only treat ACL-injured patients. Three surgeons were involved in the study, and they were selected due to their appointment as resident orthopaedic surgeons who specialise in ACL reconstruction surgery.

Immediately after surgery, players were advised to weight bear as tolerated and no brace was used. Rehabilitation was divided into early, intermediate, and advanced phases. The focus of the early phase was on controlling swelling, restoring range of motion and activation of the knee extensor and flexor muscles. The goal of the intermediate and advanced phases was to optimise muscle strength, proprioception, and neuromuscular control, and complete a phased running progression program. On completion of these phases, players took part in an on-field sports specific training and conditioning block. Routine testing and monitoring were completed during rehabilitation by an independent assessment unit to remove the potential for clinician bias. Jump monitoring commenced ~ 5 months post-surgery, following clearance from the treating physiotherapist.

Informed written consent was obtained prior to participation. This study was approved by the Institutional Review Board (IRB: F2017000227) and Research Ethics Committee (REC: 14326).

7.1.2 Experimental design

To address our stated aims, we separated our cross-sectional study into 2 components. ***In part 1,*** we compared SLDJ performance, kinetic and kinematic variables between the ACL reconstructed and uninjured limb. In ***part 2***, we examined the effect of isokinetic strength of the quadriceps and reactive strength on drop jump mechanics. For this analysis, both limbs were analysed providing the following sample size (n = 128 kinetic and n = 66 kinematic). There were fewer kinematic data available as the measurement system was introduced later following the onset of data collection for this study.

All participants were familiar with the test procedures, and we included a standardised warm-up. Each player completed 5 minutes of pulse raising activity (stationary cycling performed at 60% of maximum perceived effort) followed by 10 body weight squats (bilateral and unilateral), lunges and step ups. This was supervised by a member of the research team. Countermovement jumps were then completed at 50, 75 and 90% of perceived maximum, prior to the single leg drop jumps. Isokinetic assessments were completed ~ five minutes after the completion of the SLDJ assessment, allowing time for participant set up and practice trials. The assessment was conducted under the supervision of an experienced investigator (> 5 years using the stated test methodology).

7.1.3 Procedures

Isokinetic knee extension strength

For the detailed testing procedures used for isokinetic knee extension strength refer to Chapter 5. Five repetitions of concentric knee extension were performed at $60°\cdot s^{-1}$ with the highest peak torque value recorded (Undheim, Cosgrave, 2015). Limb order was randomized. Standardized, vigorous verbal encouragement was provided throughout.

Single leg drop vertical jump

For the detailed testing procedures used for the SLDJ refer to Chapter 5. Except for jump height and RSI in which the best score was retained, mean scores were used for the analysis. The description and method of calculation used for each variable included in this study are summarised in Table 7.1.

Peak flexion angles of the ankle, knee and hip and peak thigh angular velocity during the eccentric phase of the first landing were extracted by identifying the first eccentric peak after initial contact over the sagittal plane motion data (Pratt and Sigward, 2018a, b, Tamura et al. , 2017).

Two objective criteria were used to determine stretch shortening cycle (SSC) classification: 1) the presence of an impact peak in the athletes force-time profile (defined as the highest transient, visible force peak occurring during the first 20% of ground contact) (Pedley, Lloyd, 2020); and 2) whether they displayed spring-like behavior (defined as a Pearson product-moment correlation between vertical ground reaction force and vertical centre of mass displacement during the entire contact phase with a threshold of < -0.80) (Padua et al. , 2005). A classification of 'good' was provided when no impact peak was present, and the correlation displayed a spring-like behavior ($r \geq -0.80$). Players were deemed 'moderate' if there was an impact peak but still spring-like, *or* no impact peak was present but did not display a spring like behavior). Finally, a classification of 'poor' was given when there was an impact peak and they were not spring-like in accordance with previous research (Pedley, Lloyd, 2020).

Intraday reliability analysis was conducted. Scores were categorized as acceptable if the CV was $\leq 10\%$ (Turner, Brazier, 2015), and were further categorized as "excellent" if ICC was > 0.90, "good" between 0.75 and 0.90, "moderate" between 0.50 and 0.75, and "poor" < 0.50 (Koo and Li, 2016). All variables examined displayed "excellent" reliability scores ICC ranging from 0.9 to 0.976, and CV between 2.8 and 8.6%.

Table 7.1 Description of variables examined

Variable	**Measurement unit**	**Description**
Jump Height	cm	Maximal jump height computed using impulse-momentum method
RSI	$m \cdot s^{-1}$	Jump height divided by contact time
Relative Mean Concentric Power	$W \cdot kg^{-1}$	Mean power per kilogram during the concentric phase
Relative Mean Eccentric Power	$W \cdot kg^{-1}$	Mean power per kilogram during the eccentric phase
Concentric Impulse	$N \cdot s$	Concentric force exerted multiplied by time taken
Eccentric Impulse	$N \cdot s$	Eccentric force exerted multiplied by time taken
Force at Peak CoM Displacement	N	Force recorded at the lowest CoM position
Peak CoM displacement	m	The distance travelled by the athlete's CoM downwards during the contact time
Peak Force 1st landing	N	Highest transient, visible force peak during the landing phase
Time of Landing Peak	s	Time taken to achieve force peak during the landing phase
Time of peak CoM displacement	%	Time taken to reach the lowest CoM position
Peak ankle flexion	deg	Maximum flexion angle reached by the ankle
Peak hip flexion	deg	Maximum flexion angle reached by the hip
Peak knee flexion	deg	Maximum flexion angle reached by the knee
Thigh angular velocity	$deg \cdot s^{-1}$	Rate of change of thigh angular displacement

(RSI) reactive strength index, (CoM) center of mass, (N) Newton, (cm) centimeter, (m) meter, (W) watt, (s) second, (kg) kilogram, (deg) degree

7.1.4 Statistical analysis

The distribution of the data was checked using the Shapiro-Wilk normality test.

In ***part 1***, paired-samples tests or Wilcoxon Rank Sum Tests were used dependent on whether the data were normally distributed to examine differences in performance, kinetic and kinematic variables between the ACL reconstructed and uninjured limb. Bonferroni correction was applied to reduce the risk of type I error with multiple statistical tests. Chi-squared (χ^2) analysis was used to investigate the interaction between limbs and SSC category.

For ***part 2,*** strength and RSI thresholds were computed across players by dividing the data into tertiles, creating three groups (according to strength level: tertile 1 = "weak", tertile 2 = "moderate", and tertile 3 = "strong"; according to RSI level: tertile 1 = "low", tertile 2 = "medium", and tertile 3 = "high"). A 1-way analysis of variance (ANOVA or Kruskal–Wallis) was conducted to determine differences in SLDJ performance, and kinetic and kinematic variables between groups split according to strength levels. The same analysis was repeated with groups split according to RSI levels. Bonferroni post hoc test was used to determine pairwise differences between tertiles in the physical capacity level examined. Chi-squared (χ^2) analysis was used to investigate the interaction between groups and SSC category.

In all parts, Cohen's *d* effect sizes (ES) with 95% confidence intervals were calculated to interpret the magnitude of these differences with the following classifications: standardized mean differences of 0.2, 0.5, and 0.8 for small, moderate, and large effect sizes, respectively (Turner, Parmar, 2021b). Significance was set at $p < 0.05$. All data were computed through Microsoft Excel®2010. Data processing and descriptive statistics were processed using SPSS® (V.25. Chicago Illinois).

The statistical power when comparing the difference in kinetic variables between three independent means at an alpha of .05, was 98% for detecting a large effect size, and 70% for a moderate effect size.

7.2 Results

7.2.1 Part 1: performance, and kinetic and kinematic differences between the ACL reconstructed and uninjured limb

There were large significant differences between the ACL reconstructed and uninjured limb in SLDJ height (d = -1.05, 95%CI [-1.42, -0.67]; $p \leq 0.0001$), RSI (d = -0.94, 95%CI [-1.31, -0.57]; $p \leq 0.0001$), relative mean concentric power (d = -1.05, 95%CI [-1.43, -0.68]; $p \leq 0.0001$) and relative mean eccentric power (d = 0.92, 95%CI [0.55, 1.28]; $p \leq 0.0001$) (Table 7.2). With the exception of concentric impulse and peak force at 1st landing, all kinetic variables displayed significant between-limb differences with effect sizes range from moderate (d = -0.71) to small (d = -0.42) (Table 7.2).

All kinematic variables displayed significant between limbs differences, except for peak hip flexion (Table 7.2). The effect size ranged from moderate (d = -0.56) to small (d = -0.38). Chi-squared analysis did not reveal any significant relationship between limbs and SSC category (χ^2 (2) = 3930, p = 0.140).

Table 7.2 Performance and kinetic differences between the ACL reconstructed and uninvolved limb

Variable	ACL reconstructed limb	Uninvolved limb	Between limbs differences: effect size (95%CI) and P value
Performance			
Jump Height (m)	0.12 ± 0.019	0.14 ± 0.019	-1.05 (-1.42 to -0.67) $\boldsymbol{p < 0.0001}$
Reactive Strength Index	0.299 ± 0.07	0.369 ± 0.078	-0.94 (-1.31 to -0.57) $\boldsymbol{p < 0.0001}$
Relative Mean Concentric Power ($W \cdot kg^{-1}$)	16.67 ± 2.11	18.87 ± 2.04	-1.05 (-1.43 to -0.68) $\boldsymbol{p < 0.0001}$
Relative Mean Eccentric Power ($W \cdot kg^{-1}$)	-16.59 ± 2.56	-18.94 ± 2.52	0.92 (0.55 to 1.28) $\boldsymbol{p < 0.0001}$
Kinetic			
Concentric Impulse (N·s)	281 ± 82	274 ± 61	0.09 (-0.26 to 0.44) $p = 0.110$
Eccentric Impulse (N·s)	244 ± 57	251 ± 54	-0.14 (-0.49 to 0.21) $\boldsymbol{p = 0.002}$
Force at Peak Centre of Mass Displacement (N)	1625 ± 413	1802 ± 435	-0.42 (-0.77 to -0.06) $\boldsymbol{p < 0.0001}$
Peak CoM displacement (m)	-0.18 ± 0.03	-0.20 ± 0.04	0.69 (0.33 to 1.05) $\boldsymbol{p < 0.0001}$
Peak Force 1st landing (N)	1953 ± 450	1996 ± 440	-0.09 (-0.44 to 0.26) $p = 0.147$

Time of Landing Peak (s)	0.084 ± 0.022	0.102 ± 0.028	-0.71 (-1.08 to -0.35) ***p* < 0.0001**
Time of peak CoM displacement (%)	43.92 ± 3.74	45.93 ± 2.64	-0.62 (-0.98 to -0.26) ***p* < 0.0001**
Kinematic			
Peak ankle flexion (deg)	14.15 ± 5.61	17.08 ± 4.69	-0.56 (-1.06 to - 0.06) ***p* = 0.0008**
Peak hip flexion (deg)	47.43 ± 11.90	44.18 ± 12.89	0.26 (-0.24 to 0.75) *p* = 0.016
Peak knee flexion (deg)	53.48 ± 11.85	57.68 ± 9.90	-0.38 (-0.88 to 0.12) ***p* = 0.0009**
Thigh angular velocity ($deg \cdot s^{-1}$)	203.21 ± 90.51	236.33 ± 83.61	-0.38 (-0.87 to 0.12) ***p* = 0.002**

Significant difference between limbs: $p < 0.003$

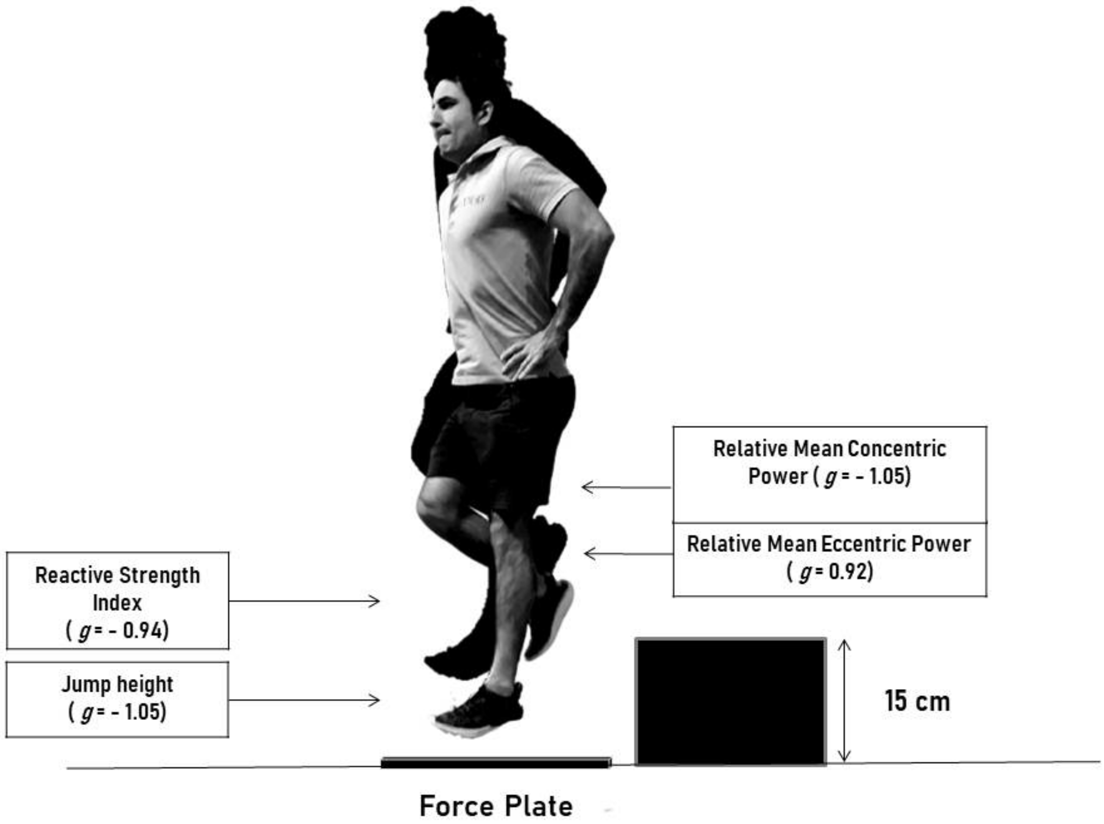


Figure 7.1 Single Leg Drop Jump performance variables of the ACL reconstructed limb (grey) in comparison with the uninvolved limb (black)

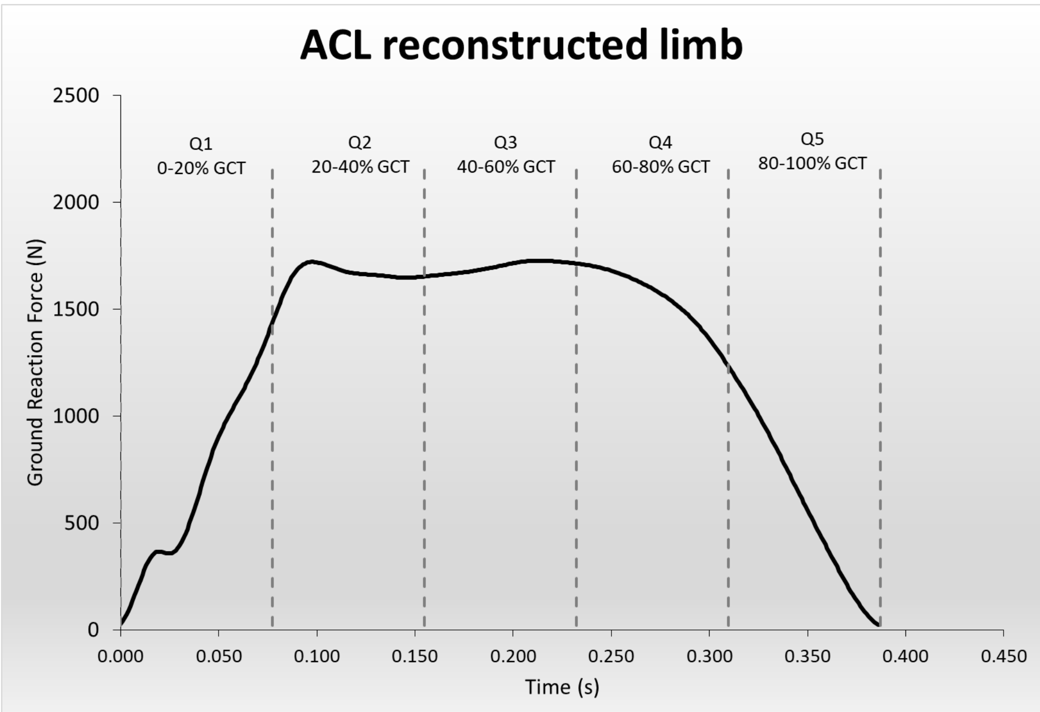


Figure 7.2 Example of a Single Leg Drop Jump force-time curve of the ACL reconstructed limb

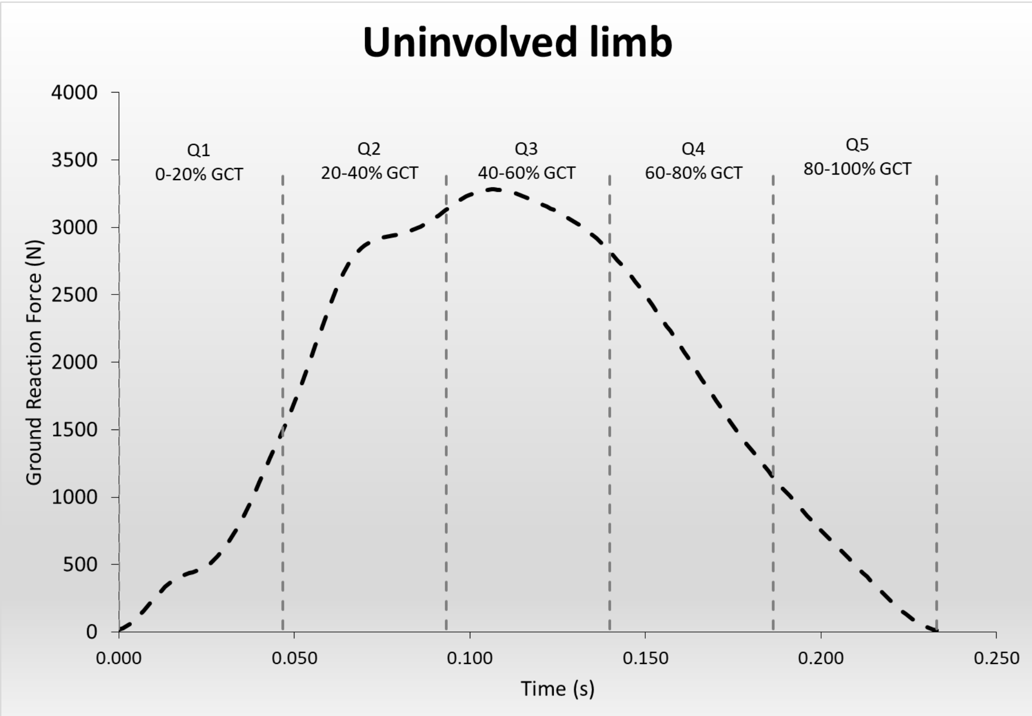


Figure 7.3 Example of a Single Leg Drop Jump force-time curve of the uninvolved limb

7.2.2 Part 2a: the effect of strength on SLDJ performance, kinetic and kinematic variables

According to strength tertiles, groups were split as follows: "weak" = $\leq$ 2.86 N·m·kg^{-1}, "moderate" = 2.87 – 3.22 N·m·kg^{-1}, and "strong" $\geq$ 3.23 N·m·kg^{-1}. There were no significant differences between the "weak" and "moderate", and "moderate" and "strong" groups. There were large statistically significant differences between the "weak" and "strong" groups in SLDJ height (d = -0.85, 95%CI [-1.30, -0.40]; p = 0.002), RSI (d = -0.93, 95%CI [-1.38, -0.48]; p = 0.002), mean concentric (d = -0.85, 95%CI [-1.30, -0.40]; p = 0.001) and eccentric power (d = 0.84, 95%CI [0.40, 1.29]; p = 0.002) (Table 7.3). Moderate differences in time of peak CoM displacement (d = -0.69, 95%CI [-1.13, -0.25]; p = 0.007), peak CoM displacement (d = 0.51, 95%CI [0.081, 0.95]; p = 0.03) and time of landing peak (d = -0.60, 95%CI [-1.04, -0.16]; p = 0.02) were also observed (Table 7.3). No significant differences in any kinematic variable were present between the "weak" and "strong" groups in SLDJ (Table 7.3).

Owing to the expected count of "poor" SSC function being less than 5, chi squared analysis could not be performed on 3 categories of SSC function. Therefore, frequency count of poor and moderate were combined to produce 2 categories of function. Chi-squared analysis did not reveal any significant relationship between strength level and SSC category (χ^2 (2) = 3873, p = 0.144), with no significant differences in the proportion of poor or moderate and good SSC category between groups.

Table 7.3 Performance, kinetic and kinematic differences between the "weak", "moderate" and "strong" group

Variable	Weak (n = 43)	Moderate (n = 42)	Strong (n = 43)	"Weak" vs "Moderate" group differences: effect size (95%CI) and P value	"Moderate" vs "Strong" group differences: effect size (95%CI) and P value	"Weak" vs "Strong" group differences: effect size (95%CI) and P value
Performance						
Jump Height (m)	0.12 ± 0.02	0.13 ± 0.02	0.14 ± 0.02	-0.48 (-0.92 to -0.05) p = 0.07	-0.49 (-0.93 to -0.05) p = 0.214	-0.85 (-1.30 to -0.40) ***p* = 0.002**
Reactive Strength Index	0.30 ± 0.08	0.33 ± 0.07	0.37 ± 0.08	-0.40 (-0.83 to 0.04) p = 0.458	-0.58 (-1.02 to -0.14) p = 0.027	-0.93 (-1.38 to -0.48) ***p* = 0.002**
Relative Mean Concentric Power (W·kg^{-1})	16.84 ± 2.77	17.58 ± 1.75	18.88 ± 2.04	-0.32 (-0.75 to 0.12) p = 0.371	-0.70 (-1.14 to -0.25) p = 0.023	-0.85 (-1.30 to -0.40) ***p* = 0.001**
Relative Mean Eccentric Power (W·kg^{-1})	-16.78 ± 3.07	-17.43 ± 2.49	-19.08 ± 2.27	0.23 (-0.20 to 0.66) p = 0.770	0.69 (0.24 to 1.13) p = 0.014	0.84 (0.40 to 1.29) ***p* = 0.002**
Kinetic						
Concentric Impulse (N·s)	287 ± 102	281 ± 53	264 ± 45	0.07 (-0.36 to 0.50) p = 0.654	0.35 (-0.09 to 0.78) p = 0.128	0.29 (-0.14 to 0.72) p = 0.228
Eccentric Impulse (N·s)	244 ± 66	257 ± 55	241 ± 42	-0.21 (-0.64 to 0.22) p = 0.229	0.33 (-0.11 to 0.76) p = 0.199	0.06 (-0.37 to 0.49) p = 0.935
Force at Peak Centre of Mass Displacement (N)	1657 ± 415	1680 ± 380	1802 ± 489	-0.06 (-0.49 to 0.37) p = 0.909	-0.28 (-0.71 to -0.16) p = 0.334	-0.32 (-0.75 to 0.12) p = 0.298
Peak CoM displacement (m)	-0.18 ± 0.04	-0.20 ± 0.04	-0.2 ± 0.04	0.51 (0.08 to 0.95) p = 0.019	-0.00 (-0.43 to 0.43) p = 0.799	0.51 (0.08 to 0.95) p = 0.03
Peak Force 1st landing (N)	2033 ± 526	1908 ± 319	1980 ± 461	0.28 (-0.15 to 0.72) p = 0.257	-0.18 (-0.61 to 0.25) p = 0.745	0.11 (-0.32 to 0.54) p = 0.487
Time of Landing Peak (s)	0.084 ± 0.027	0.090 ± 0.027	0.100 ± 0.026	-0.22 (-0.65 to 0.21) p = 0.343	-0.37 (-0.81 to 0.06) p = 0.744	-0.60 (-1.04 to -0.16) p = 0.02

Time of peak CoM displacement (%)	43.48 ± 3.48	45.6 ± 3.36	45.7 ± 2.84	-0.61 (-1.06 to -0.17) $p = 0.016$	-0.03 (-0.46 to 0.40) $p = 0.732$	-0.69 (-1.13 to -0.25) $p = 0.007$
Kinematic						
Peak ankle flexion (deg)	14.31 ± 6.3	15.7 ± 4.6	16.83 ± 4.92	-0.25 (-0.86 to 0.36) $p = 1.000$	-0.23 (-0.84 to 0.38) $p = 1.000$	-0.44 (-1.05 to 0.18) $p = 0.365$
Peak hip flexion (deg)	48.77 ± 12.87	43.6 ± 11.3	45.03 ± 12.96	0.42 (-0.20 to 1.03) $p = 0.519$	-0.12 (-0.72 to 0.49) $p = 1.000$	0.28 (-0.33 to 0.90) $p = 0.965$
Peak knee flexion (deg)	52.39 ± 12.2	56.1 ± 9.3	58.26 ± 11.09	-0.34 (-0.95 to 0.28) $p = 0.132$	-0.21 (-0.82 to 0.40) $p = 0.392$	-0.49 (-1.11 to 0.12) $p = 0.132$
Thigh angular velocity (deg·s^{-1})	214.73 ± 105.99	212.3 ± 65.3	232.27 ± 90.85	0.03 (-0.58 to 0.64) $p = 0.597$	-0.25 (-0.86 to 0.36) $p = 0.606$	-0.17 (-0.78 to 0.44) $p = 0.644$

Significant difference between limbs: $p < 0.003$

7.2.3 Part 2b: the effect of reactive strength on SLDJ performance, kinetic and kinematic variables

According to RSI tertiles, groups were split as follows: “low” = ≤ 0.29, “medium” = 0.30 – 0.38, and “high” ≥ 0.39. There were no statistically significant differences between the “low” and “medium” RSI groups, except for jump height (d = -0.79, 95%CI [-1.24, -0.34]; p = 0.0007). There were significant differences corresponding to a very large effect size between the “medium” and “high” RSI groups in relative mean concentric (d = -2.89, 95%CI [-3.51, -2.27]; p = 0.002) and eccentric power (d = 3.36, 95%CI [2.68, 4.03]; p = 0.003). Moderate differences were shown in force at peak CoM displacement (d = -0.75, 95%CI [-1.19, -0.30]; p = 0.0008)

There were statistically significant differences corresponding to a very large effect size between the “low” and “high” RSI group in SLDJ height (d = -1.54, 95%CI [-2.03, -1.05]; $p \leq$ 0.0001), relative mean concentric (d = -3.67, 95%CI [-4.38, -2.96]; $p \leq 0.0001$) and eccentric power (d = 3.94, 95%CI [3.20, 4.68]; $p \leq 0.0001$), (Table 7.4).

Large differences in force at peak CoM displacement (d = -1.30, 95%CI [-1.77, -0.82]; $p \leq$ 0.0001), concentric (d = 0.91, 95%CI [0.46, 1.36]; $p \leq 0.0001$) and eccentric impulse (d = 0.88, 95%CI [0.43, 1.33]; $p \leq 0.0001$) were evident between the two groups. Moderate and small differences were shown in time of landing peak (d = -0.65, 95%CI [-1.09, -0.21]; p = 0.014) and peak force 1st landing (d = -0.49, 95%CI [-0.92, -0.05]; p = 0.005) respectively (Table

7.4). No significant between groups differences were present in peak CoM displacement and time of peak CoM displacement.

Peak hip flexion showed large differences between groups (*d* = 0.91, 95%CI [0.28, 1.55]; (*p* = 0.014). No significant difference in any other kinematic variable was present between the "low" and "high" RSI groups in SLDJ (Table 7.4). Chi-squared analysis revealed a significant relationship between RSI level and SSC category (χ^2 (2) = 13713, *p* = 0.001). The "high" RSI group had a greater proportion of "good" SSC function (77%) in comparison with the "low" RSI group (37%).

Table 7.4 Performance, kinetic and kinematic differences between the "low", "medium" and "high" RSI group

Variable	Low (n = 43)	Medium (n = 42)	High (n = 43)	"Low" vs "medium" group differences: effect size (95%CI) and P value	"Medium" vs "high" group differences: effect size (95%CI) and P value	"Low" vs "high" group differences: effect size (95%CI) and P value
Performance						
Jump Height (m)	0.12 ± 0.02	0.13 ± 0.02	0.14 ± 0.02	-0.79 (-1.24 to -0.34) ***p* = 0.0007**	-0.67 (-1.12 to -0.23) *p* = 0.006	-1.52 (-2.20 to -0.83) ***p* < 0.0001**
Relative Mean Concentric Power (W·kg^{-1})	15.38 ± 1.54	17.60 ± 0.74	20.32 ± 1.09	-1.81 (-2.33 to -1.30) *p* = 0.209	-2.89 (-3.51 to -2.27) ***p* = 0.002**	-3.59 (-4.58 to -2.61) ***p* < 0.0001**
Relative Mean Eccentric Power (W·kg^{-1})	-14.86 ± 1.86	-17.60 ± 0.86	-20.83 ± 1.03	1.87 (1.35 to 2.39) *p* = 0.140	3.36 (2.68 to 4.03) ***p* = 0.003**	3.84 (2.81 to 4.87) ***p* < 0.0001**
Kinetic						
Concentric Impulse (N·s)	313 ± 98	275 ± 48	245 ± 35	0.47 (0.04 to 0.91) *p* = 0.654	0.72 (0.77 to 1.16) *p* = 0.128	0.88 (0.25 to 1.51) ***p* < 0.0001**
Eccentric Impulse (N·s)	272 ± 70	247 ± 47	224 ± 32	0.42 (-0.02 to 0.85) *p* = 0.229	0.58 (0.14 to 1.02) *p* = 0.199	0.85 (0.22 to 1.49) ***p* < 0.0001**
Force at Peak Centre of Mass Displacement (N)	1471 ± 309	1680 ± 340	1988 ± 466	-0.64 (-1.08 to -0.20) *p* = 0.035	-0.75 (-1.19 to -0.30) ***p* = 0.0008**	-1.30 (-1.97 to -0.64) ***p* < 0.0001**
Peak CoM displacement (m)	-0.20 ± 0.04	-0.20 ± 0.04	-0.18 ± 0.03	-0.02 (-0.46 to 0.41) *p* = 1.000	-0.53 (-0.97 to -0.09) *p* = 0.174	-0.55 (-1.16 to 0.06) *p* = 0.069

Peak Force 1st landing (N)	1892 ± 526	1905 ± 334	2125 ± 419	-0.03 (-0.46 to 0.40) $p = 0.257$	-0.57 (-1.01 to -0.13) $p = 0.745$	-0.48 (-1.09 to 0.13) $p = 0.005$
Time of Landing Peak (s)	0.085 ± 0.028	0.090 ± 0.023	0.103 ± 0.027	-0.19 (-0.63 to 0.24) $p = 0.157$	-0.51 (-0.95 to -0.07) $p = 0.250$	-0.64 (-1.26 to -0.02) $p = 0.014$
Time of peak CoM displacement (%)	44.48 ± 4.29	44.87 ± 3.42	45.41 ± 2.05	-0.10 (-0.53 to 0.33) $p = 1.000$	-0.19 (-0.62 to 0.24) $p = 1.000$	-0.27 (-0.87 to 0.34) $p = 0.623$
Kinematic						
Peak ankle flexion (deg)	14.72 ± 6.4	15.40 ± 5.19	17.01 ± 3.92	-0.11 (-0.72 to 0.49) $p = 1.000$	-0.34 (-0.95 to 0.27) $p = 0.856$	-0.42 (-1.03 to 0.19) $p = 0.464$
Peak hip flexion (deg)	51.33 ± 11.39	44.27 ± 13.16	41.03 ± 10.75	0.57 (-0.05 to 1.18) $p = 0.148$	0.26 (-0.34 to 0.87) $p = 1.000$	0.91 (0.28 to 1.55) $p = 0.014$
Peak knee flexion (deg)	57.90 ± 12.54	53.13 ± 9.78	55.38 ± 10.34	0.41 (-0.20 to 1.02) $p = 0.459$	-0.22 (-0.82 to 0.38) $p = 1.000$	0.21 (-0.39 to 0.82) $p = 1.000$
Thigh angular velocity ($deg \cdot s^{-1}$)	210.13 ± 99.05	204.33 ± 69.12	246.24 ± 89.67	0.07 (-0.54 to 0.67) $p = 0.597$	-0.52 (-1.13 to 0.09) $p = 0.606$	-0.37 (-0.98 to 0.23) $p = 0.078$

Significant difference between limbs: $p \leq 0.003$

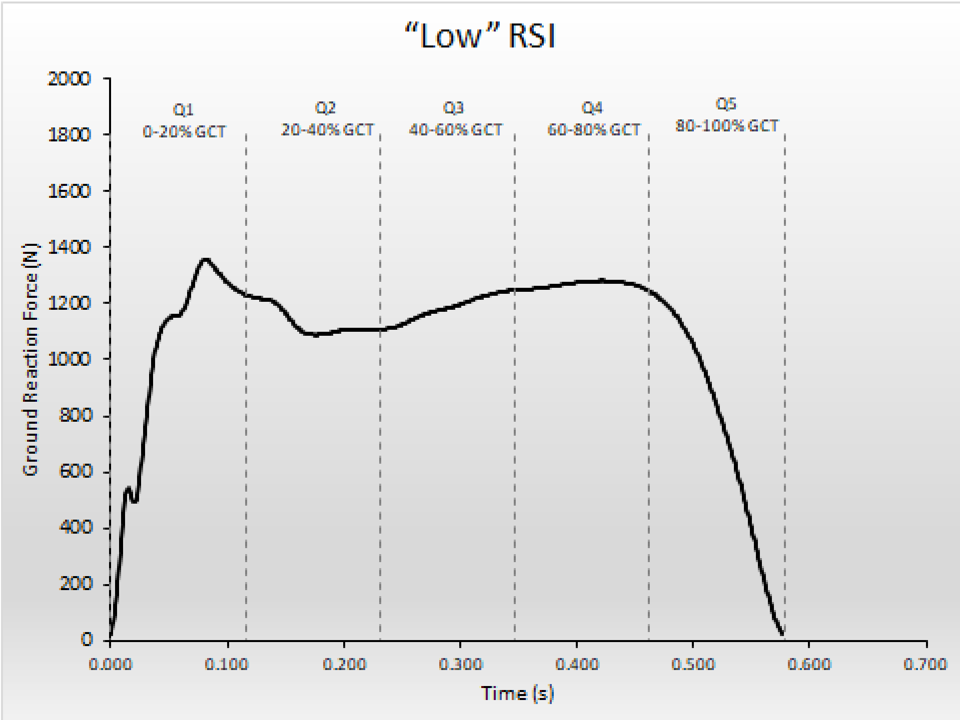


Figure 7.4 Example of a Single Leg Drop Jump force-time curve of a player displaying "low" RSI

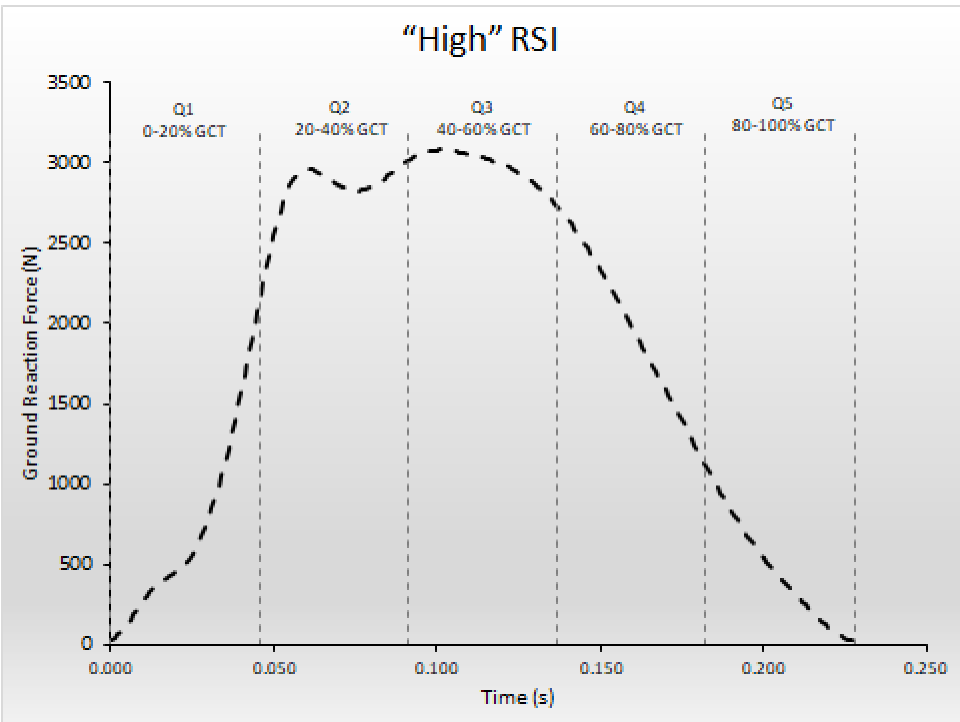


Figure 7.5 Example of a Single Leg Drop Jump force-time curve of a player displaying "high" RSI

7.3 Discussion

The aims of this study were to 1) investigate performance, kinetic and kinematic differences between the ACL reconstructed limb and the uninvolved limb; and 2) examine the effect of knee extension isokinetic strength and reactive strength levels on single leg drop jump mechanics. The results showed that in the ACL reconstructed limb, all performance metrics were reduced, and most kinetic and kinematic variables differed between limbs despite players being in the final stages of rehabilitation ~ 8 months post-surgery. Knee extension isokinetic strength level revealed large and moderate differences in performance metrics and kinetic variables respectively, whereas RSI level more clearly displayed performance and biomechanical variables typically associated with impaired SSC function and increased re-injury risk.

The inclusion of the SLDJ assessment in the late phase of rehabilitation has been suggested to better highlight deficits in knee function compared to single leg countermovement and horizontal jumps in male athletes at the time of RTS (King, Richter, 2018b, King, Richter, 2019, Kotsifaki, Van Rossom, 2022). Quantifying SSC performance can determine an athlete's ability to efficiently store and reutilise elastic energy during high eccentric stretch loads, such as landing and change of direction, which are crucial for sports performance across a range of field sports (Brughelli et al. , 2008), and have also been identified as primary actions in non-contact ACL injuries (Dos'Santos, Thomas, 2018, Fox, 2018, Marques, Paul, 2019). Our results strengthen previous findings (King, Richter, 2018b, Kotsifaki, Van Rossom, 2022, Lloyd, Oliver, 2020, Read, Davies, 2020a), showing that jump height, reactive strength, and relative concentric and eccentric mean power are reduced in the ACL reconstructed limb in comparison to the uninvolved limb. We also observed kinetic and kinematic differences between limbs in SLDJ execution, typically associated with higher re-injury risk. In particular, CoM displacement was reduced, and peak landing force occurred in the earlier stages of ground contact. This resulted in a lower thigh angular velocity, and peak ankle and knee flexion angles, thus adopting a "stiff" knee movement strategy commonly documented in male athletes following ACL reconstruction and associated with higher risk of re-injury (Maestroni, Papadopoulos, 2021a).

The reduction of thigh angular velocity observed suggests an intra-limb compensation strategy for lower peak power generation at the knee, concomitant with reduced knee flexion ROM excursion. Pratt et al. (Pratt and Sigward, 2018b) showed that peak thigh angular velocity was the best predictor of knee power absorption (R^2 = 66%) after initial ground contact during single limb loading. Cumulatively, this may indicate the need at the time of RTS of a more controlled active deceleration of the body's CoM, through enhanced pre-activation strategies and more efficient utilisation of stretch-reflexes (Bhattacharyya, 2017, Gollhofer et al. , 1984). Earlier activation of active constraints and enhanced neuromuscular control strategies may help to optimise the force-time profile, reducing the presence of an impact peak; thus, absorbing and recycling large peak braking forces more efficiently through the entire ground contact phase. Our analysis reinforced the notion that performance and biomechanical assessment of SLDJ provide useful information to assess knee function in the late stage of rehabilitation and at the time of RTS, with implications for sports performance readiness and rehabilitation status. In addition, wearable technology, such as IMUs used for this study, identified similar kinematic strategies recently reported using three-dimensional motion capture [3, 10]. This may aid in bridging the gap between lab and field-based methods; however, more research is needed to validate thigh angular velocity using IMU sensors during a SLDJ task following ACL reconstruction.

Deficits in peak knee extension torque are commonly displayed in the ACL reconstructed limb at the time of RTS (Johnston, McClelland, 2020, Maestroni, Read, 2021b). The most common assessment mode includes the use of isokinetic peak torque at $60°\cdot s^{-1}$ (Undheim, Cosgrave, 2015), with practice recommendations to restore knee extension strength > $3.0\ N\cdot m\cdot kg^{-1}$, as minimum requirement of a rehabilitation programme (van Melick, van Cingel, 2016, van Melick et al. , 2022). Our results indicate that, players who produced lower peak knee extension torque (< $2.86\ N\cdot m\cdot kg^{-1}$) displayed reduced SLDJ performance, shallower CoM displacement (d = 0.51) and peak knee flexion angles (d = -0.49), with peak landing force occurring earlier during the ground contact phase (d = -0.60) than stronger players > $3.23\ N\cdot m\cdot kg^{-1}$. This movement strategy, characterized by an impaired capacity to effectively attenuate landing velocity in the lower extremity, has been associated with poorer tibiofemoral articular cartilage composition and matrix degeneration following ACL reconstruction (Brunst et al. , 2022, Pfeiffer et al. , 2021). Therefore, it appears that a "stiff" knee movement strategy to offload the knee joint is more likely present in weaker than stronger athletes at the time of RTS, thus highlighting the importance of quadriceps strength recovery during rehabilitation.

Players with "high" RSI scores (≥ 0.39) displayed greater performance metrics (i.e., jump height, relative concentric and eccentric power) and more advantageous biomechanical characteristics compared to players with "low" RSI (≤ 0.29), suggesting larger magnitude differences in RSI affect ground reaction force and spring-like characteristics. Our tertiles categorization reflected values previously shown in 268 male soccer players (Read, Davies, 2020a), and thus such cut-offs can be used to benchmark SSC performance recovery. Higher SSC performance is associated with a reduced metabolic cost of running and enhanced change of direction performance (Li, Newton, 2019, Maloney, Richards, 2017), but also with a lower risk of ipsilateral and contralateral ACL injury (King, Richter, 2021a, b). In our cohort, those displaying "low" RSI scores appeared to show less frequently spring-like behavior, recorded a landing peak earlier during ground contact (d = -0.64), and absorbed less force in the eccentric phase, but over a longer contact time, which was evident in the higher eccentric impulse recorded (d = 0.85). This absorbing motion does not exploit the advantages of elastic energy and stretch reflexes during the initial phase of landing (Oh and Lee, 2022), and occurred through higher deformation of the CoM coming from greater hip flexion angles (d = 0.91), which is a typical intra-limb compensation strategy adopted during single leg dynamic tasks in ACL reconstructed cohorts (Maestroni, Papadopoulos, 2021a).

Our data were limited to adult male professional football players. Therefore, generalisation of these results to paediatric, adolescent, and female athletes requires caution. Our strength assessment did not include distal components nor closed chain tasks. Soleus contribution was recently found lower in ACL reconstructed male athletes during the propulsion phase of vertical jumps (Kotsifaki, Van Rossom, 2022), and may be more strongly correlated with performance and biomechanics of fast SSC actions than quadriceps strength (Möck et al. , 2018). Furthermore, there is potential for deterioration of the uninvolved contralateral limb following surgery due to deconditioning/lack of exposure (Wellsandt, Failla, 2017a), which may overestimate rehabilitation status if symmetry scores are solely considered and a control group is not included. The main purpose of this study was to examine how differences in strength and RSI effect drop jump ground reaction force characteristics. We included kinematic data to provide further and more descriptive analysis. However, due to the reduced sample, our findings should be interpreted with caution (in particular when effect sizes are small) and warrants further research. In addition, although the IMU system has been validated for several single leg loading tasks (Pratt and Sigward, 2018a, b, Vervaat et al. , 2022), confirmation of these findings during the SLDJ assessment warrants further investigation. In particular, IMU system measurement errors within the examined variables need to be established before concluding that meaningful differences have occurred.

Between-limb differences in SLDJ performance, kinetics and kinematics are present in the later stages of rehabilitation following ACL reconstruction. These deficits were more apparent in male soccer players who displayed lower isokinetic knee extension torque and SLDJ RSI. The involved limb displayed a "stiff" knee movement strategy, characterised by lower thigh angular velocity, reduced CoM displacement, and peak landing force occurring in the earlier stages of ground contact, which is associated with higher risk of re-injury (Maestroni, Papadopoulos, 2021a). Our findings suggest that targeted interventions to improve maximal strength and plyometric ability are needed at the appropriate stages during rehabilitation (Królikowska, Reichert, 2019, Maestroni, Read, 2020, Welling, Benjaminse, 2019) to enhance the modulation of the SSC (Haff and Nimphius, 2012, Maloney, Richards, 2019), and to improve eccentric force generation capacity. For example, single joint (e.g., leg extension) and multi joint exercises (e.g. split squat) can be utilised to normalise inter-limb asymmetries in force production. External load of strength exercises should be regularly progressed to optimise strength levels according with normative values (Oliveira et al. , 2022, Welling, Benjaminse, 2019). Likewise, plyometric training can be progressed according to the athlete's strength level, fatigue, technique competency and rehabilitation phase (Suchomel et al. , 2019b). The initial focus is placed on exercises that emphasise eccentric storage capacity while landing, prior to progression of rebound spring like actions with short ground contact times. Finally, practitioners may wish to select activities that utilise kinetic energy recycling with increasing intensities of the eccentric stimulus (Flanagan and Comyns, 2008). Progressive plyometric training is performed both bilaterally and unilaterally in vertical, horizontal and lateral directions to match the braking, propulsive and medio-lateral forces typical of change of direction tasks and sprinting actions (Asadi, Arazi, 2016, Brughelli, Cronin, 2008, Haugen et al. , 2019, Maloney, Richards, 2017). For detailed information regarding practical applications to return athletes to high performance we recommend recently published articles (Buckthorpe, 2019, Buckthorpe and Della Villa, 2019, Maestroni, Read, 2020, Welling, Benjaminse, 2019). Examples of progressive SSC drills that can be used according to rehabilitation stage, load tolerance and physical competencies can also be found in our recent article (Turner et al. , 2022).

Whereas studies 1 and 2 provide a greater understanding of the recovery in physical capacities and their effect on biomechanics, an overall representation of our professional soccer players- physical preparedness was needed. Therefore, we created a composite score including absolute strength, reactive strength and power characteristics and explored its value and utility for RTS decision making and subsequent injury risk identification. In addition, it remains unclear if lower levels of physical capacity are associated with subsequent injury. Thus, we used a case series to examine the composite scores of players who re-injured following their RTS.

CHAPTER 8: Empirical STUDY 3

Total Score of Athleticism: profiling strength and power characteristics in professional soccer players following Anterior Cruciate Ligament Reconstruction to assess return to sport readiness

In this chapter our aim was to utilise a different approach to profiling athlete readiness instead of purely limb symmetry which is standard in RTS testing. Thus, we investigated whether a composite score (TSA) including strength and power qualities differed between ACL reconstructed players and healthy controls. In addition, we assessed the predictive ability of the TSA to identify group membership, and we discussed the characteristics of individuals who sustained a subsequent injury within 4 months following their RTS. This study was published in The American Journal of Sports Medicine

Maestroni, L., Turner, A., Papadopoulos, Sideris, V., & Read, P. (2023). Total Score of Athleticism: profiling strength and power characteristics in professional soccer players following Anterior Cruciate Ligament Reconstruction to assess return to sport readiness. American Journal of Sports Medicine.

8.0 Introduction

One year following ACL reconstruction, most elite soccer players return to play (> 90%) (Della Villa et al. , 2021, Waldén and Hägglund, 2016); however, only two thirds compete at the same pre-injury level three years later (Niederer, Engeroff, 2018, Waldén and Hägglund, 2016, Zaffagnini et al. , 2014). ACL injury has been associated with cartilage compositional changes and early joint degeneration in young individuals (Li et al. , 2013, Li et al. , 2011, Su et al. , 2013), and having had ACL reconstruction is a risk factor for future injury in multidirectional field sport athletes (OR 2.2; 95% CI 1.1–4.4; p = 0.029) (Messer et al. , 2022). ACL reconstructed elite soccer players also display a nearly 20-fold increased risk for sustaining a subsequent ipsilateral or contralateral rupture in comparison to matched healthy players

(Niederer, Engeroff, 2018). Reduced reactive strength (King, Richter, 2021b) and knee extension strength (Grindem, Snyder-Mackler, 2016) are modifiable risk factors associated with secondary injury.

Male ACL reconstructed soccer players display reduced strength, power and reactive strength absolute values in the operated limb in comparison to healthy controls (Maestroni, Read, 2021b, O'Malley, Richter, 2018, Read, Davies, 2020a, Read, Michael Auliffe, 2020b). Assessment of these fundamental physical characteristics can help practitioners to quantify neuromuscular qualities that underpin movements inherent to soccer such as sprinting, jumping, and change of direction (Haff and Stone, 2015, Jones, Bampouras, 2009). Owing to different multidimensional aspects involved with RTS (Cronström et al. , 2022), there is no consensus on when an athlete is ready to RTS, or the optimal testing procedure to determine sport readiness (Buckthorpe, 2019). Current practice (van Melick, van Cingel, 2016) involves a battery of strength and hop tests, with a limb-symmetry index of ≥ 90% recommended as the cut-off point to determine 'pass' or 'fail' (Burgi, Peters, 2019a, Kyritsis, Bahr, 2016). However, this does not consider potential performance decrements of the uninvolved limb following injury and surgery, thus limiting the utility of this approach (Burgi, Peters, 2019a, Kyritsis, Bahr, 2016). Research has shown that a low proportion of patients (23%) also pass these RTS criteria (i.e., based on symmetry scores ≥ 90%), but do still return to play (Webster and Hewett, 2019). Furthermore, only a minority of non-injured athletes 'pass' these tests meeting the ≥ 90% symmetry criteria (~24%) (Markström et al. , 2022). This may be due to the reduction in pass probability when multiple tests across a number of domains are added into a battery, limiting the utility of this approach for the purpose of augmenting RTS decision making (Webster and Hewett, 2019).

Rather than separately analysing each individual test result using pre-determined symmetry thresholds, a composite score encompassing different performance characteristics can be calculated for each player. This approach has already been adopted in fitness testing, using standardized scores from a series of tests to create a single Total Score of Athleticism (TSA) for each individual player (Turner, Jones, 2019). By averaging standardized scores (e.g., *z* scores) and applying the TSA instead of just inter-limb symmetry in different tests, this allows clinicians and coaches to examine contextualized data of individual athletes relative to their teammates and thus, set benchmarks for return to sport readiness that are realistic to the demands athletes will be exposed to. Oleksy et al. (Oleksy et al. , 2021) showed reduced composite scores (albeit using Functional Movement Screen, Y-Balance test and Tuck Jump assessments) in Polish ACL reconstructed players in comparison to healthy controls. However, these do not primarily examine the physical characteristics underpinning athletic movements related to injury risk. The utility of this novel approach using absolute strength and power qualities has yet to be examined in athletic populations aiming to RTS following ACL reconstruction and the completion of rehabilitation.

This study aimed to 1) investigate if there are differences in TSA between ACL reconstructed and uninjured players; 2) examine the predictive ability of the TSA to identify group membership (ACL reconstruction vs. healthy controls); and 3) include a case series to discuss the characteristics of individuals who having undergone ACL reconstruction, sustained a subsequent injury within 4 months following their RTS.

8.1 Methods

8.1.1 Participants

60 male soccer players participating in the Qatar Stars and Qatar Gas Leagues (25.1 ± 12.6 years; 175.8 ± 9.2 cm; 74.3 ± 14 kg) at an average of 9.2 (± 3) months post ACL reconstruction, volunteered to take part in this study. Most ACL grafts were bone-patella-tendon bone (80%), with the remaining players (20%) all semitendinosus and gracilis hamstring tendon grafts. Inclusion criteria required players to have no history of previous ACL injury / surgery, or other knee ligament or cartilage injury / surgery of either the operated or non-operated leg. All participants were involved in an intensive supervised rehabilitation programme (5 days per week) at the same sports medicine hospital (Kyritsis, Bahr, 2016), commencing immediately post operation, and were required to have completed the early, intermediate and advanced phases of rehabilitation and be actively involved in on-field, sports specific rehabilitation. The focus of the early phase was on controlling swelling, restoring range of motion and activation of the knee extensor and flexor muscles. The goal of the intermediate and advanced phases was to optimise muscle strength, proprioception, and neuromuscular control, and complete a phased running progression program. On completion of these phases, players took part in an on-field sports specific training and conditioning block. Informed written consent was obtained prior to participation.

We also recruited thirty-five (uninjured) matched controls (23.8 ± 2.8 years; height = 173.8 ± 5.4 cm; weight = 71.6 ± 6.3 kg) from the same leagues who attended pre-season screening at the national sports medicine institution and were randomly selected from a pool of 300 athletes.

Inclusion was based on having no history of ACL injury and being free from any severe injury (defined as > 28 days' time-loss) in the previous 12 months, verified via a national injury audit. Clubs competing in the stated leagues within Qatar regularly complete formalised strength and conditioning including resistance training, speed, agility and plyometrics. The data collected for the ACL participants was collected across 2017-2020. Data for the healthy controls were collected in 2017 at the onset of the study. This study was approved by the Institutional Review Board (IRB: F2017000227) and Research Ethics Committee (REC: 14326).

8.1.2 Experimental design

To address our stated aims, we: 1) calculated the TSA using standardized scores of performance variables obtained from isokinetic strength assessment (i.e., knee extension and flexion relative peak torque of both limbs), and from bilateral (CMJ) and single leg countermovement jump test (SLCMJ) (i.e., jump height, relative peak power and reactive strength modified [RSImod]) and then compared the TSA between ACL reconstructed and uninjured players; 2) examined the ability of the TSA to identify group membership (ACL reconstructed or uninjured group) and; 3) completed a case series of ACL reconstructed players who had further injuries in the first 4 months following completion of rehabilitation and RTS. This time period was chosen to avoid the confounding effects of regular soccer training and seasonal variation on strength and power characteristics (Bishop et al. , 2022).

All participants were familiar with the test procedures and completed a standardised warm-up consisting of 5 minutes of pulse raising activity (stationary cycling performed at 60% of maximum perceived effort) followed by 10 body weight squats (bilateral and unilateral), lunges and step ups. Countermovement jumps were then completed at 50, 75 and 90% of perceived maximum (Read, Auliffe, 2021). Isokinetic assessments were completed after the jump test battery. The assessment was conducted under the supervision of an experienced investigator (> 5 years using the stated test methodology).

8.1.3 Injury reporting

The Orthopaedic and Sports Medicine centre involved in this study provides medical and sports science services to all sport clubs in the country. As part of this programme, it is mandatory to report any injuries that occur to players in their hospital medical record. Furthermore, a national injury audit is completed annually and coordinated by the hospitals research department. The research department also employed a research assistant to work as part of the ACL assessment pathway who contacted all players as part of a routine follow up every three months following RTS. Injuries were recorded if they resulted in time-loss from their sport, and all were confirmed via magnetic resonance imaging (MRI) at the same Orthopaedic and Sports Medicine Hospital. A time loss injury was classified as an occurrence resulting in days lost from training sessions and matches.

8.1.4 Test Procedures

Isokinetic knee extension and flexion strength

For the detailed testing procedures used for isokinetic knee extension and flexion strength refer to Chapter 5

Five repetitions of concentric knee extension and flexion were performed at 60°/s with the highest peak torque value recorded (Undheim, Cosgrave, 2015). Peak torque values were reported as a percentage of the individual's body mass. No formal familiarization sessions was completed, but each participant had previous experience of isokinetic testing with regular monitoring throughout their rehabilitation.

Countermovement Jump (bilateral/single)

For the detailed testing procedures used for CMJ and SLCMJ refer to Chapter 5**.**

Jump height was calculated from the impulse-momentum relationship derived take off velocity and equation of constant acceleration (velocity at take-off squared divided by 2*9.81 ($v^2/2g$). Peak power was measured and normalized to bodyweight Watt/kg (Peak Power Rel) during the propulsion phase. Reactive strength index modified (RSImod), was calculated by dividing jump height by contraction time (determined from movement onset to time to take off) (Suchomel, Bailey, 2015). This variable was used to determine the ability to store and reutilize elastic energy during stretch shortening cycle activities (Flanagan and Comyns, 2008).

Total score of athleticism (TSA)

For the detailed testing procedures used for the TSA refer to Chapter 5

The TSA is a measure used across sports and performance settings (Philipp et al. , 2022, Wing et al. , 2020) including athletes returning from ACL reconstruction (Oleksy, Mika, 2021). The use of z-scores allows clinicians to compare data across similar athletes, who share the same training approach, demands, and constraints. Therefore, test scores are assumed achievable by all athletes and thus represent realistic targets and thresholds that can be worked towards. In order to define these benchmarks therefore, injured athletes must be measured alongside their 'healthy' teammates (matched controls). Furthermore, it should be noted that the TSA (and all individual z-scores) is a relative score that cannot be applied to a different group and thus compared across sports and pre published normative tables. Instead, the TSA defines how an athlete ranks amongst their teammates, who are similarly affected by a club's training philosophy and resources, and thus may highlight injured athletes who still display performance decrements and are thus not ready to return to sport. Finally, the TSA is a composite score of the chosen tests, which is further influenced by the weighting of those tests. For example, more tests maybe included that measure strength than endurance, and thus the TSA score will have a bias toward strength. The tests must therefore be chosen appropriately and are likely based on the experience of the clinicians and the type of injury. In summary, the TSA is specific to the tests chosen as well as the group tested, whereby the deviation from the mean (represented by 0), which is expressed in SD units, is likely to be the only transferable value that may be inferred to other clinical practices.

8.1.5 Statistical analysis

The distribution of the data was checked using the Kolmogorov–Smirnov normality test. Descriptive statistics (mean ± SD) for all variables were calculated.

An independent samples t-test was used to examine differences in anthropometrics and TSA between the ACL reconstructed and uninjured group. Cohen's d effect size (ES) with 95% confidence intervals (CIs) were calculated to interpret the magnitude of these differences with the following classifications: standardized mean differences of 0.2, 0.5, and 0.8 for small, moderate, and large effect sizes, respectively.

Binary logistic regression was used to examine the predictive ability of the TSA in identifying group membership (ACL reconstructed or uninjured group). Unstandardized coefficients (β) and adjusted R^2 values were reported. Odds ratios (ORs) were calculated via logistic regression with 95% CIs. Statistical significance was set at $p < 0.05$. All data were computed through Microsoft Excel®2010. Data processing and descriptive statistics were processed using SPSS® (V.25. Chicago Illinois).

TSA results were divided into tertiles (tertile 1 = "low", tertile 2 = "medium", and tertile 3 = "high"). Visual inspection of players distribution, performance characteristics and clinical history of ACL reconstructed players who had further injuries within 4 months following RTS were used for discussion.

8.2 Results

TSA was significantly lower in the ACL reconstructed group compared to those who were uninjured (d = 0.84, 95%CI [0.40, 1.27]; $p < 0.0001$) (Table 8.1). The logistic regression analysis showed that the TSA accounted for 20% of the variability observed in group membership ($R^2 = 0.200$). For every additional increase of one unit in the TSA ($\beta = -1.357$), the odds of belonging to the ACL reconstructed group decreased by 74% (95%CI 0.19, 0.56). (Table 8.2). Seven of the 60 included ACL reconstructed players suffered from a further injury within 4 months following RTS. The distribution of re-injured players is graphically represented in figure 7.1. Frequency of re-injured players was higher in the "low" (4/7) in comparison to the "medium" (2/7) and "high" (1/7) TSA tertiles. From the 7 players identified (mean RTS 8.8 ± 1.7 months), a total of 13 subsequent injuries were documented. Among these 5 included articular cartilage and meniscal injuries, whereas the remaining 8 were classified as soft tissue injuries. No ipsilateral or contralateral ACL injuries were documented during our selected time period.

Table 8.1 Anthropometric, demographic and performance differences between ACL reconstructed and uninjured players

Variable	ACL reconstructed players (n = 60)	Uninjured players (n = 35)	Between groups differences: effect size (95%CI) and P value
Age	25.1 ± 12.6	23.8 ± 2.8	0.12 (-0.30 to 0.53) $p = 0.578$
Height (cm)	175.8 ± 9.2	173.8 ± 5.4	0.25 (-0.17 to 0.67) $p = 0.180$
Weight (kg)	74.3 ± 14.0	71.6 ± 6.3	0.23 (0.19 to 0.65) $p = 0.199$
TSA	-0.20 ± 0.76	0.35 ± 0.43	0.84 (0.40 to 1.27) $\boldsymbol{p < 0.0001}$
Time from surgery (weeks)	40 ± 12		
Re-injured players within 4 months since discharge	7/60		

Significant difference between groups: $p < 0.05$

Table 8.2 Linear regression result to determine ACL group membership (n = 95, $R^2 = 0.200$)

	Odds ratio (95% CI)	P value
TSA	0.257 (0.118 – 0.561)	< 0.001

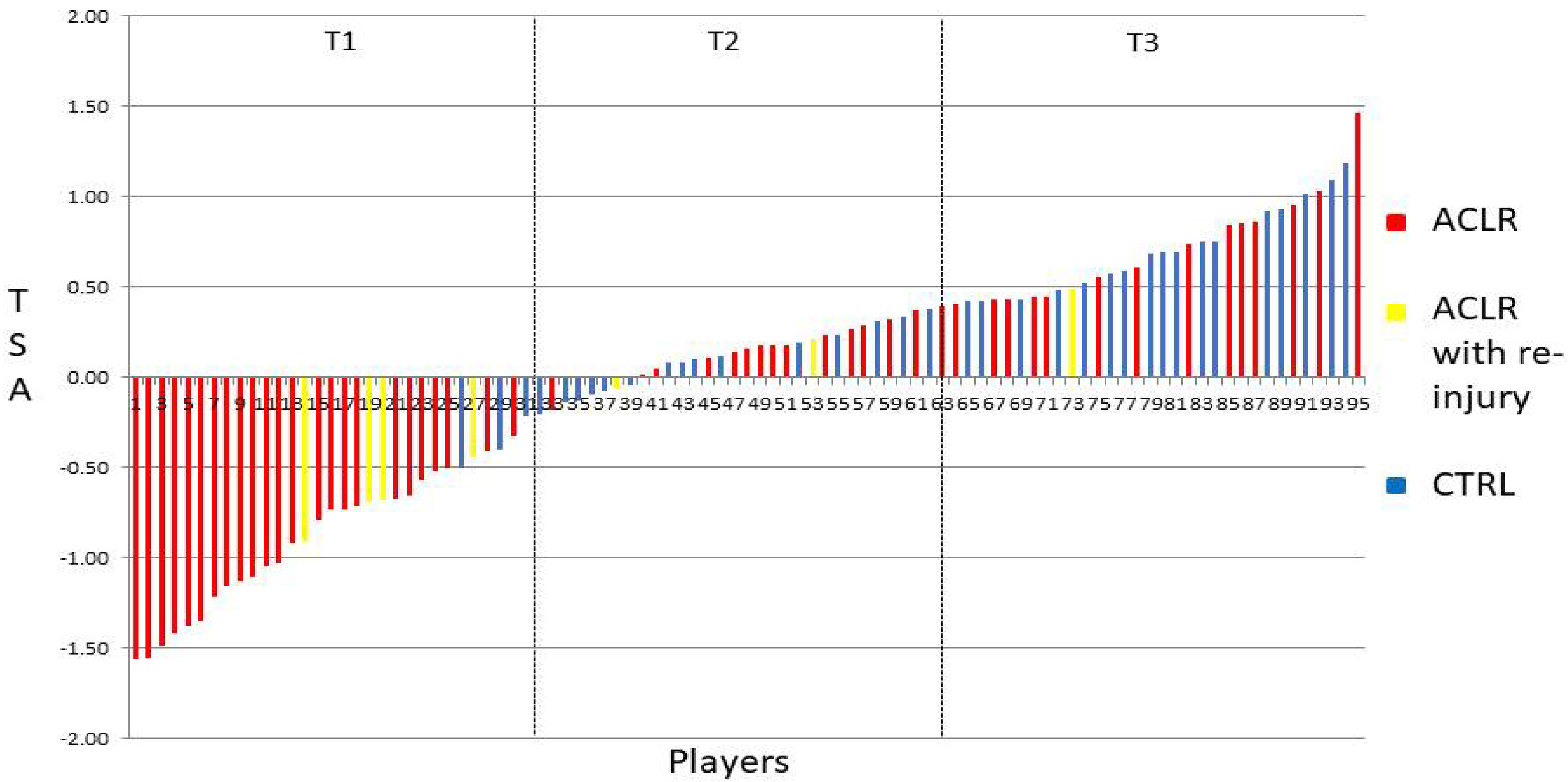


Figure 8.1 - Total score of Athleticism (TSA) of Anterior Cruciate Ligament reconstructed players who did not suffer from re-injuries (ACLR), Anterior Cruciate Ligament reconstructed players who suffered from re-injuries (ACLR with re-injury) and healthy controls (CTRL). (T) tertile

8.3 Discussion

The aims of this study were to 1) investigate differences in TSA (derived of strength and power measures) between ACL reconstructed players at the time of RTS and those competing at the same level of play who were uninjured; 2) examine the association between the TSA scores and group membership (ACL reconstructions vs. uninjured controls); and 3) complete a case series using the TSA among ACL reconstructed players who had further injuries within 4 months following RTS.

The results showed the TSA was substantially lower (d = 0.84, 95%CI [0.40, 1.27]) than healthy controls at the time of RTS. Lower scores in the examined physical qualities (i.e., strength, power and reactive strength) have been associated with reduced performance in more complex athletic skills, such as pivoting, cutting, landing, jumping, which are critical to soccer athleticism and RTS (Cormie, McGuigan, 2011a, b). Using the TSA to determine physical readiness may overcome some of the limitations associated with RTS testing. Firstly, the TSA avoids the need for passing tests using symmetry alone, reducing overestimation of recovery (using the potentially deteriorated contralateral limb) (Moran et al. , 2022, Wellsandt, Failla, 2017a), and includes comparative data from matched healthy controls. Furthermore, this approach avoids the normal reduction in pass probability when there is a requirement to obtain a specific score across multiple tests. Importantly, the TSA allows judgement of single test scores within a measure of general performance level, instead of binary “pass” or “fail” criteria. This allows contextualization of a single player’s data in relation to their teammates, and can be used to set benchmarks, and rehabilitation goals which are realistic during rehabilitation for restoration of physical performance to a level no lesser than uninjured players, and are reflective of the RTS demands (Turner, Jones, 2019).

The regression analysis showed that the TSA accounted for 20% of the variability observed in players status identification. Although the optimal testing procedure to determine sport readiness is currently unclear (Buckthorpe, 2019), our results confirm the utility of an overall measure of contextualized physical preparedness before RTS to differentiate between injured and un-injured players. Indeed, the odds of shifting towards a ‘healthy’ player’s profile increase with TSA improvements. For every 0.5 increase in TSA the odds of belonging to the ACL reconstructed group decrease by 49%. A change of 1 unit decreases the odds of being in the ACL group by 74%. To understand which specific component of the total score needs specific attention, each physical characteristic can be broken down and further analysed, by using z-scores and respective threshold values (Table 8.3).

Table 8.3 Physical characteristics threshold for our cohort in each tertile

Tertile	CMJ Jump Height (cm)	CMJ Rel Peak Power (W/kg)	CMJ RSImod (m/s)	SLCMJ height UNINV (cm)	SLCMJ Rel Peak Power UNINV (W/kg)	SLCMJ RSImod UNINV (m/s)	SLCMJ height INV (cm)	SLCMJ Rel Peak Power INV (W/kg)	SLCMJ RSImod INV (m/s)	Rel Knee Extension Strength UNINV (Nm/kg)	Rel Knee Extension Strength INV (Nm/kg)	Rel Knee Flexion Strength UNINV (Nm/kg)	Rel Knee Flexion Strength INV (Nm/kg)	TSA
First	< 33.5	< 47.4	< 0.39	< 16.1	< 29.3	< 0.18	< 14.0	< 27.5	< 0.16	< 3.0	< 2.8	< 1.6	< 1.6	< -0.20
Second	33.5 to 36.3	47.4 to 52.6	0.39 to 0.47	16.1 to 19.2	29.3 to 33.0	0.18 to 0.24	14.0 to 17.5	27.5 to 30.6	0.16 to 0.21	3.0 to 3.4	2.8 to 3.1	1.6 to 1.9	1.6 to 1.9	-0.20 to 0.39
Third	> 36.3	> 52.6	> 0.47	> 19.2	> 33.0	> 0.24	> 17.5	> 30.6	> 0.21	> 3.4	> 3.1	> 1.9	> 1.9	> 0.39

0 visualization using a simple figure schematic (see for example figures 8.2, 8.3 and 8.4) can be a logical and simple way to understand weaknesses and strengths of each individual player (i.e., scores below or above zero indicating an athlete being worse or better than average), and can be used to identify one or multiple components to be targeted to collectively increase the TSA during specific rehabilitation and training cycles (Turner, Jones, 2019). Pragmatically, bars below zero represent opportunities for improvement that should be targeted during rehabilitation before RTS to achieve important, safe and specific physical qualities thresholds, and to increase the TSA overall.

8.4 Case series analysis

ACL injuries can have a detrimental effect on individual athletic performance and this may increase subsequent injury risk (Messer, Williams, 2022, Niederer, Engeroff, 2018). Current evidence indicates equivocal findings that passing current RTS criteria are associated with a reduction in the risk of ipsilateral graft or contralateral ACL subsequent ruptures (Bodkin et al. , 2022, Kyritsis, Bahr, 2016, Losciale, Zdeb, 2019b, Webster and Hewett, 2019, Welling et al. , 2020). The preliminary findings of our case series showed that among the 7 ACL reconstructed players who sustained a further injury within 4 months following RTS, only 1 player displayed a relatively "high" TSA. The other players were either in the "low" (4/7) or "medium" (2/7) TSA tertiles, suggesting higher composite scores encompassing strength and power capacities may be protective towards further articular cartilage, meniscal and soft tissue injuries at the time of RTS. We elected to complete a case series as our sample size was not large enough to examine these associations using regressions analysis.

To demonstrate the practical utility of the TSA we have compared three players and also demonstrated how a targeted test-training integration process can be used to optimise readiness to RTS. Player 14 (18^{th} percentile, TSA = -0.91, 30 years old, 166 cm, 58 kg, hamstring graft, 9.5 months post-surgery) (see figure 8.1 and 8.2), displayed lower power (CMJ relative power = 41.2 W/kg, jump height = 25.4 cm) and reactive strength (CMJ RSImod = 0.30) characteristics within our cohort. Also, these did not meet currently available reference values (i.e., jump height = 34.5 ± 4.0 cm and relative power = 50.4 ± 4.9 W/kg) (Read, Michael Auliffe, 2020b). In addition, he showed lower relative peak knee flexion strength (1.70 Nm/kg) of the ACL reconstructed limb when compared to the rest of the group. At about 2 months following RTS, he was diagnosed with deep chondral fissure and distal biceps femoris myotendinous junction strain injury on the involved limb. Maladaptive functioning of the dampening mechanisms have been demonstrated following ACL reconstruction (Read, Pedley, 2022a). This can impair force attenuation during fast sporting actions such as jumping, landing, and change of direction, exposing athletes to large impact forces, which have been associated with more deleterious compositional changes in the articular cartilage of the tibiofemoral compartment (Pfeiffer, Spang, 2021). Similarly, athletes with a history of ACL reconstruction and lower knee flexor strength have higher probability of future hamstring strain injury than stronger athletes (Messer, Williams, 2022), and knee flexor strength deficits are more pronounced in those who elect for a hamstring graft (Maestroni, Read, 2021b). For this player it seems reasonable to suggest targeted interventions prior to RTS may have been warranted to improve maximal strength, power and plyometric ability (Królikowska, Reichert, 2019, Maestroni, Read, 2020, Welling, Benjaminse, 2019) to enhance the modulation of the SSC (Haff and Nimphius, 2012, Maloney, Richards, 2019), and to improve general strength as well as knee flexion force generation capacity before RTS.

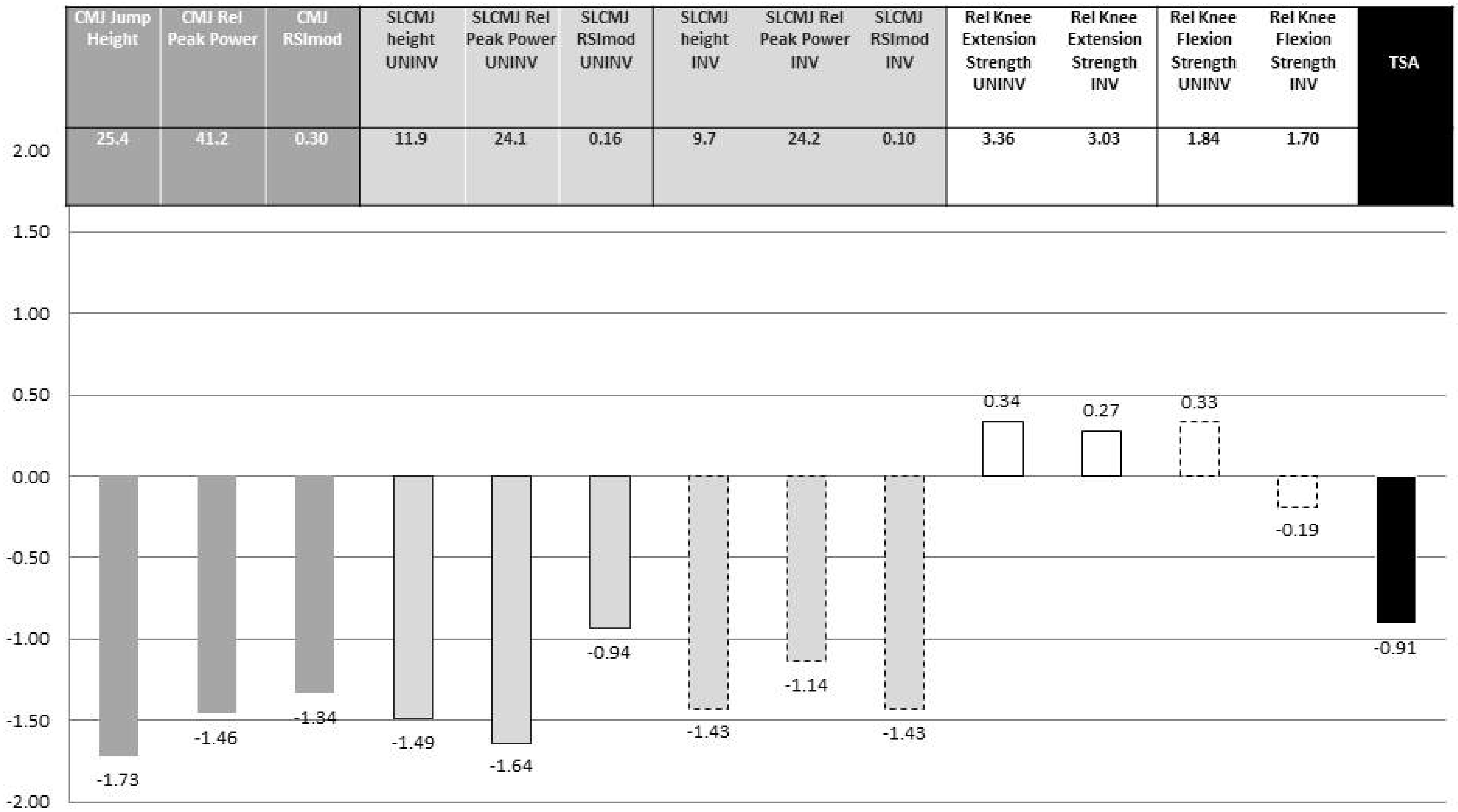


Figure 8.2 Player 14 strength, power and reactive strength values and standardized scores

Similar power (CMJ relative power = 43.1W/kg, jump height = 29.1 cm) and reactive strength (CMJ RSImod = 0.33) characteristics were displayed by player 20 (25th percentile, TSA = -0.68, 21 years old, 174 cm, 80 kg, bone patellar tendon bone graft, 8.5 months post-surgery) (see figure 8.1 and 8.3). Low bilateral relative peak knee extension strength values (involved limb = 2.15 Nm/kg, uninvolved limb = 2.84 Nm/kg) were also shown compared to the rest of the cohort. At approximately 3 months following RTS, he reported a bucket handle medial meniscus tear in the ACL reconstructed knee. This player could have benefited from targeted strength and power training, with a particular focus on restoring knee extension strength until at least normative values were reached (i.e., 3.0 Nm/kg) (Welling, Benjaminse, 2019).

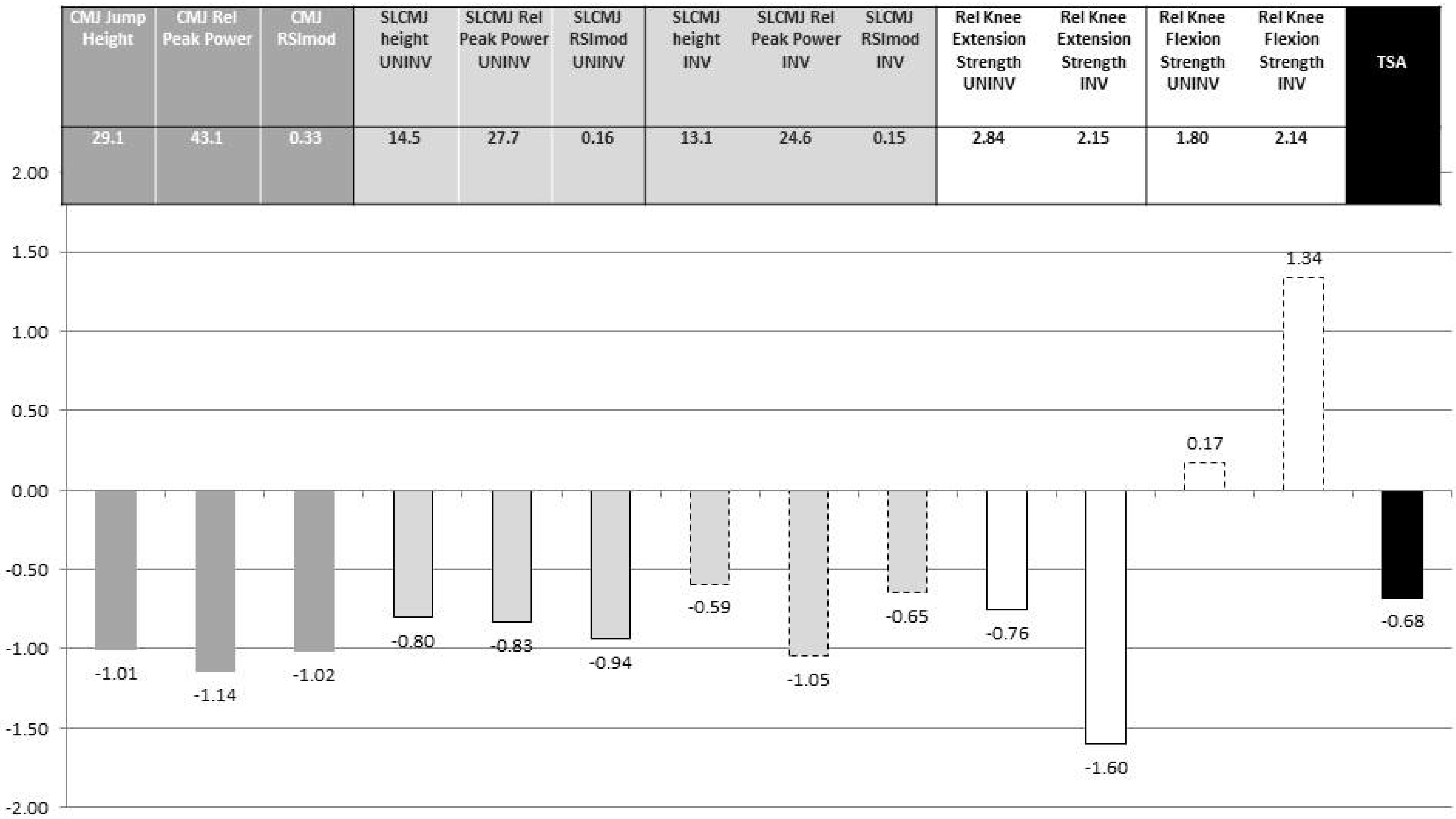


Figure 8.3 Player 20 strength, power and reactive strength values and standardized scores

Player 73's TSA score was in the first tertile (69th percentile, TSA = 0.49, 22 years old, 180 cm, 73 kg, bone patellar tendon bone graft, 10.2 months post surgery) (see figures 8.1 and 8.4), yet he sustained a grade 1 hamstring strain injury of the uninvolved limb at around 4 weeks following RTS. He showed above average strength (relative peak knee extension strength = 3.49 Nm/kg, relative peak flexion strength = 2.03 Nm/kg), power (SLCMJ relative power = 33.3 W/kg, jump height = 17.9 cm) and reactive strength qualities (SLCMJ RSImod = 0.27) on the uninvolved limb, but these were not matched by the ACL reconstructed limb (with the exception of relative peak knee extension strength = 3.38 Nm/kg). In the absence of details to examine his soccer training programs, match schedules and training volume, it may be speculated that reduced physical qualities on his ACL reconstructed limb (SLCMJ relative power = 30.1 W/kg, jump height = 14.9 cm, SLCMJ RSImod = 0.19, relative peak knee flexion strength = 1.78 Nm/kg) could have resulted in abnormal sagittal mechanics of the ACL reconstructed limb at the stance phase of running commonly found at RTS (Pairot-de-Fontenay et al. , 2019), requiring compensatory strategies and creating higher stress on the hamstring muscles in the contralateral limb. Therefore, it may have been prudent to develop single leg posterior chain strength, plyometric and power training, can be accompanied by running drills to facilitate the integration of the newly acquired qualities into the cyclical motion of running and sprinting (Turner, Read, 2022).

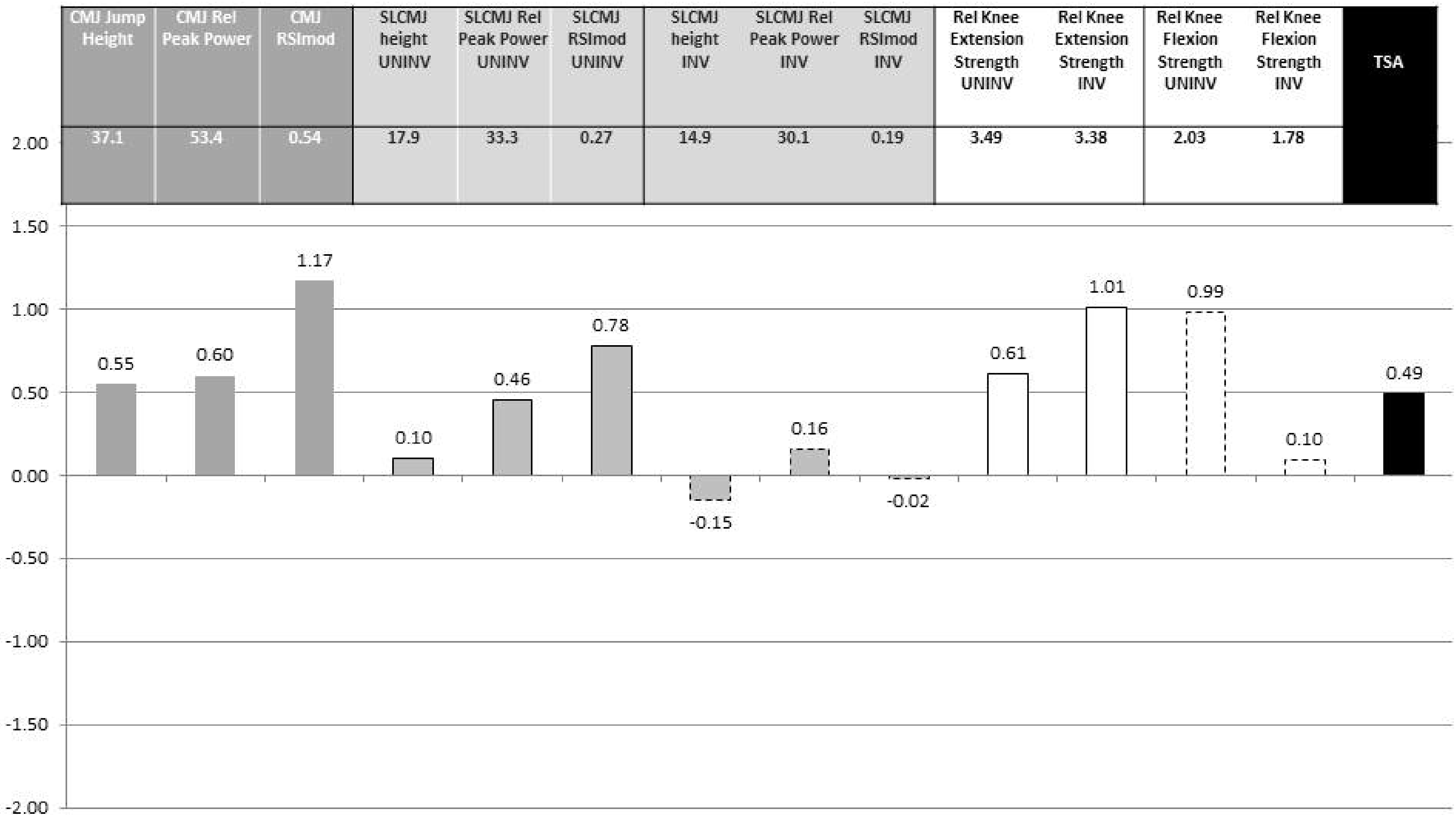


Figure 8.4 - Player 73 strength, power and reactive strength values and standardized scores

The tests included in this study were limited to those routinely used to assess an athlete's current level of physical capacity related to ACL research (Maestroni, Read, 2021b). However, the TSA can and should encompass a broader range of aspects (e.g., hip and ankle strength, aerobic capacity, psychological readiness, agility, etc.). While TSA provides an overall indication of general sport readiness, it is also prudent to examine movement strategies that may be associated with re-injury risk (King, Richter, 2018a, King, Richter, 2019). Therefore, analysis of the athlete's kinetics and kinematics during task execution is also advised. Similarly, we only extracted peak torque values from our isokinetic strength assessment, and further angle-specific analysis could be included to more accurately identify residual deficits could be recommended (Hart et al. , 2022, Read et al. , 2022b). Clinicians should also consider psychological readiness (McPherson, Feller, 2019), and ensure that the requisite training volume representative of a player's sports demands have been met in a progressive manner throughout their return to sport journey (Riboli et al. , 2022). Although it may be assumed that training and game exposure among our players were similar, detailed access to exposure data were not available and should be considered in further studies.

Our data were also limited to adult male football players. However, TSA results are related to the cohort, sport and tests assessed, and thus could be generalized to paediatric, adolescent and female athletes. Finally, although for the integration of TSA in clinical practice only a commonly available spreadsheet software (e.g., Microsoft Excel) is needed, contextualisation of players TSA at the time of RTS following ACL reconstruction with matched controls requires enough healthy players test scores to be readily available. Therefore, it is recommendable to routinely undertake RTS tests encompassing strength, power, and reactive strength qualities each season across the largest possible number of players. This allows benchmark data to be stored (including pre-injury values) and this can be used to generate the TSA. Owing to seasonal variations in strength and power characteristics, periodic assessments at later time-points (> 4 months following RTS) are recommended to further explore implications of the TSA with long-term subsequent injuries risk (Bishop, Abbott, 2022). Future research may wish to examine if lower TSA scores are associated with increased injury risk in larger athletic cohorts.

8.5 Conclusion

The findings of the current study indicate that a composite score (TSA) including strength, power and reactive strength characteristics differed between elite soccer players at the time of RTS following ACL reconstruction and healthy matched controls. TSA could be used to determine physical readiness, discriminate players status, and can be readily used by healthcare and sports professionals to identify the achievable targets needed during rehabilitation for restoration of physical performance relative to peers competing at the same level. Preliminary data indicates doing so has positive implications for lowering subsequent injury risk, but further research is required to more clearly elucidate these findings in larger cohorts and using statistical modelling.

CHAPTER 9 – Discussion, Practical Applications and Directions for Future Research.

9.1 Overall summary

The research presented in this thesis has significant implications for optimizing both the rehabilitation process and the athletes return to performance journey by more fully examining how patient readiness to re-perform is assessed. Firstly, the data presented in empirical study 1 provides a clear trajectory of the recovery of physical capacities in athletic soccer populations participating in a structured rehabilitation program following ACL reconstruction. Secondly, the findings of empirical study 2 can enhance future rehabilitation programs by more fully understanding how fundamental physical capacities underpin movement strategies during athletic performance tasks in soccer players with a history of ACL reconstruction. Thirdly, empirical study 3 can be used to aid in the development of more holistic and comprehensive athletic performance criteria, relating performances to those of matched controls from a representative athletic population. This approach can increase the validity and utility of RTS testing to determine patient outcomes including subsequent injury risk following ACL reconstruction

9.2 Key findings and practical applications

9.2.1 Literature Reviews

The literature review (chapter 2) showed that deficits in maximal strength, rate of force development (RFD), and reactive strength are commonly reported following several musculoskeletal injuries. These are also common in athletes following ACL reconstruction despite rehabilitation guidelines (Adams et al. , 2012a, van Melick, van Cingel, 2016) including criterion-based progressions to protect healing structures, ensure safe restoration of fundamental physical capacities, and guide appropriate return to sports activities. Negative deficits on knee peak extension and flexion strength, respectively, are present in male adults at more than 6 months post ACL reconstruction (chapter 3). The magnitude of these differences is influenced by graft type and can be mitigated by targeted rehabilitation programs. Insufficient evidence is available in male adults following anterior cruciate ligament reconstruction to examine rate of force development and reactive strength, with further research recommended. In addition, deficits in knee extensor torque are associated with inter-limb and intra-limb compensation strategies indicative of greater re-injury risk (chapter 4) (Ithurburn, Paterno, 2015, Lisee, Birchmeier, 2019a, Miles and King, 2019, O'Malley, Richter, 2018, OberlÄNder, BrÜGgemann, 2013, Paterno, Ford, 2007, Paterno, Schmitt, 2010, Schmitt, Paterno, 2015). Therefore, it appears of the utmost importance that strategies to increase maximal quadriceps strength are an integral component of rehabilitation. This synthesis of the available literature guided our approach in developing the empirical studies in this thesis and we hope other researchers will also utilise these findings to develop future projects to investigate the areas identified further.

9.2.2 Study 1

Our findings indicate that ACL reconstruction has a detrimental effect on strength and power characteristics in professional soccer players, albeit with diverse recovery patterns displayed. Peak knee extension strength, CMJ and SLCMJ height, RSImod, and relative peak power values at the end of rehabilitation prior to RTS remained below those recorded pre-injury. Conversely, these were either preserved or improved in the uninjured limb following rehabilitation. Furthermore, even though players approached strength values deemed sufficient in the ACL reconstructed limb (i.e., peak knee extensor torque > 3.0 Nm/kg and peak knee flexors torque > 1.8 Nm/kg) and exceeded these criteria in the contralateral limb, large differences in SLCMJ height and RSImod were still evident on the ACL reconstructed limb in comparison to uninjured matched controls. These disparities were smaller when assessed bilaterally (i.e., CMJ test), indicating that SLCMJ may be more sensitive to identify between-limb differences and can be used as a key diagnostic test to evaluate the recovery of individual limb physical capacity.

Cumulatively, our findings have clinical implications that can be used to guide future practice in RTS testing and monitoring during rehabilitation. To determine physical recovery at the time of RTS we suggest to: 1) collect data as early as possible (baseline pre-injury if available or if not pre-operative values on the uninvolved limb) to inform readiness to RTS as this should be considered the gold standard reducing the need for proxy measures of limb recovery, which can overestimate or underestimate limb function; 2) consider both absolute scores on each limb and not just symmetry values; 3) in situations where baseline pre-injury data are not available, compare to uninjured matched controls to ensure minimum standards are met . In addition, we suggest including both unilateral and bilateral assessments with a range of demands across the strength, power, and velocity spectrum to ensure performance is measured under different task constraints.

9.2.3 Study 2

A key finding which is consistent with other research (King, Richter, 2018b, Read, Davies, 2020a) showed moderate to large differences between the ACL reconstructed and uninjured limb in SLDJ performance, kinetic and kinematic variables. More novel contributions are evident in our data that show athletes with greater knee extension strength jump higher and produce greater concentric and eccentric power. Similar findings were present for RSI, but the effects were larger. Weaker players, and those who had lower RSI, displayed landing mechanics indicative of a "stiff" knee movement strategy. Players with lower knee extension strength and RSI exhibited reduced performance and kinetic strategies that have previously been associated with increased injury risk (Ithurburn, Paterno, 2015, Lisee, Birchmeier, 2019a, Miles and King, 2019, O'Malley, Richter, 2018, OberlÄNder, BrÜGgemann, 2013, Paterno, Ford, 2007, Paterno, Schmitt, 2010, Schmitt, Paterno, 2015). These are characterised by lower thigh angular velocity, reduced CoM displacement, and peak landing force occurring in the earlier stages of ground contact.

We suggest that that targeted interventions which are progressive in nature are needed to improve maximal strength and plyometric ability that consider stage of rehabilitation (Królikowska, Reichert, 2019, Maestroni, Read, 2020, Welling, Benjaminse, 2019) and the level of patient function to enhance the modulation of the SSC (Haff and Nimphius, 2012, Maloney, Richards, 2019), and improve eccentric force generation capacity.

9.2.4 Study 3

Our findings indicate the Total Score of Athleticism (TSA), which is a composite score including strength, power, and reactive strength assessments, is lower in soccer players at the end of rehabilitation following ACL reconstruction in comparison to healthy controls. The TSA allows contextualization of a single player's data in relation to their teammates, and can be used to set benchmarks, and rehabilitation goals which are realistic during rehabilitation for restoration of physical performance to a level no lesser than uninjured players and are reflective of the RTS demands. This can aid RTS decision making, and a higher TSA may be protective towards further articular cartilage, meniscal and soft tissue injuries.

The TSA could be used to determine physical preparedness, discriminate players status, and identify achievable targets during rehabilitation for the restoration of physical performance relative to their peers competing at the same level. Preliminary data indicates doing so has positive implications for lowering subsequent injury risk, but further research is required to elucidate these findings more clearly in larger cohorts. Once the required components of performance are identified, targeted reconditioning strategies to improve maximal strength and/or ballistic performance are needed at the appropriate stages during rehabilitation (Królikowska, Reichert, 2019, Maestroni, Read, 2020, Welling, Benjaminse, 2019). The components underpinning physical preparedness are not independent variables. Therefore, each phase of rehabilitation should have a clear emphasis that provides a valuable foundation for more complex sporting skills. A training emphasis infers that a larger proportion of the mesocycle is utilised to improve a specific biomotor component, while the others are maintained as best as possible (Turner et al. , 2021a). For example, a relatively weaker individual would benefit most from an emphasis on strength training, whereas a stronger individual would benefit most from an emphasis on ballistic training, even though both qualities may be included during specific rehabilitation phases. In this last scenario, strength is still trained and maintained as best as possible, although with much less volume, but with the same frequency and intensity. This research highlights how fundamental physical qualities are necessary for athletes following ACL reconstruction to return to compete at their full athletic potential and reduce consequent articular cartilage, meniscal, and soft tissue injuries, albeit the latter requires further research to elucidate more clearly.

9.3 Directions for future research

Based on the findings of the research included in this thesis, there are several areas that could be investigated in the future. Owing to their closer association with landing and change of direction tasks, future research could prospectively monitor rebounding tasks (e.g., SLDJ) performance and biomechanics in a cohort of professional soccer players to investigate whether these can better identify players at higher risk of ACL injury, and consequently analyse their recovery patterns using pre-injury data also.

Secondly, there is an absence of research to examine movement tasks associated with prospective injury risk measured using wearable technology, and no data in adult male multidirectional field sports athletes. Also, the IMU system has been validated for several single leg loading tasks (Heuvelmans et al. , 2022, Pratt and Sigward, 2018a, b, Vervaat, Bogen, 2022), but confirmation of these findings during the SLDJ assessment warrants further investigation.

Finally, although our preliminary findings showed that higher composite scores (TSA) encompassing strength and power capacities may be protective towards further articular cartilage, meniscal and soft tissue injuries at the time of RTS, a more comprehensive TSA including a broader range of physical capacities (e.g. aerobic fitness, speed, change of direction, etc.) may have greater validity.

9.4 Conclusion

Overall, our research findings demonstrated that strength, power, and reactive strength characteristics of professional soccer players at the later stages of rehabilitation and at RTS following ACL reconstruction are still not fully recovered. We encourage collection of routine preinjury data to most accurately determine performance recovery. Reductions in knee extension strength and stretch shortening cycle function had a negative effect on drop jump biomechanics, indicative of movement characteristics typically associated with greater risk of re-injury. Finally, a composite score of strength and power measures was able to differentiate between group status (ACLR vs healthy controls), and athletes who sustained a reinjury following RTS were more represented in lower tertiles; thus, composite profiling may more fully represent physical readiness and rehabilitation status and overcome the limitations of using test batteries and symmetry indexes.

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Appendices

Appendix A – Ethical approval forms

Anti- Doping Lab Qatar Institutional Review Board

Tel: 44132988
Fax: 44132997

IRB MoPH Registration: SCH-ADL-070
MoPH Assurance: MOPH-A-ADL-Q-071

APPROVAL NOTICE

Date	1st Nov, 2017
Lead Principal Investigator	**Paul J. Read; Sean Mc Aullife - Aspetar**
Co-PI	**Mathew Wilson, Roald Bahr, Scott Gillogly, Rodney Whitely, Philippe Landreau**
IRB Application #	F2017000227
Site/s	**Aspetar**
Funding Entity	**Aspetar**
Protocol Title	**Factors associated with ACL injury, successful rehabilitation outcomes and return to sport following ACL reconstruction in athletic populations.**
Submission Type	**Initial Submission**
Review Type	**Full Board**
Approval Period	**1st Nov, 2017– 31st Oct, 2018**

The Anti-Doping Lab Qatar Institutional Review Board has reviewed and approved the above referenced protocol. As the Principal Investigator of this research project, you are responsible for:

- Ethical compliance and protection of the rights, safety and welfare of human subjects involved in this research project.
- To follow the policies and procedures as set by ADLQ-IRB in any matters related to the project, following the ADLQ-IRB approval which includes:-
- Obtaining prior approval of any modifications to the approved protocol including the change of research team members.
- Reporting deviations and unanticipated events; major deviations within 24 hours.
- Renewing Ethics annually or every six months if IRB requires it.
- Submission of progress reports annually
- Informing the ADLQ-RO of the date of commencement of the research.

ADLQ IRB Chair
Dr. Yorck Olaf Schumacher

مختبر مكافحة المنشطات قطر
Anti Doping Lab Qatar

** For Commencement of Research, Protocol Deviation Reporting, Unanticipated Problem Reporting & Research Progress Annual Report, please contact - Education & Research Office, Anti-Doping Lab Qatar.*

ADLQ RESEARCH OFFICE
P.O.BOX 27775
Email: ADLQ-RO@adlqatar.com

- We may contact you regarding studies you may be interested in participating.
- We want to assure you that we will keep your information confidential.
- You do not have to be in this study if you do not want to participate.
- Your decision to be in any study is totally voluntary.
- Your care at Aspetar will not be altered by your decision to participate or not participate.
- Your information will not be shared outside of this study team except to those groups inside and outside of Anti-Doping Lab Qatar, who are responsible for making sure that studies are conducted correctly and ethically.

If you are interested in learning more about the study, please contact either Dr. Paul Read (paul.read@aspetar.com) or Dr. Sean Michael Auliffe (sean.auliffe@aspetar.com)

Complete the attached questions and mail it back to us using the self-addressed and stamped envelope. (***the questions (related to your study) must be submitted with the advertisement to the IRB for review***).

Review the attached consent form *(link to ADULT CONSENT FORM)* and call the numbers below so that a researcher can talk with you about the study and answer your questions.

Sincerely,

Dr. Paul Read
Principal Investigator
IRB#F2017000227

Contact No: 44132283

THIS STUDY HAS BEEN REVIEWED AND APPROVED BY ANTI-DOPING LAB QATAR INSTITUTIONAL REVIEW BOARD

IRB APPROVAL STAMP
مختبر مكافحة
المنشطات قطر
Anti Doping
Lab Qatar

Anti- Doping Lab Qatar Institutional Review Board

Tel: 44132988
Fax: 44132997

IRB MoPH Registration: SCH-ADL-070
MoPH Assurance: MOPH-A-ADL-Q-071

APPROVAL NOTICE
[Ethics Approval Renewal]

Date	**30th Oct, 2018**
Lead Principal Investigator	**Paul J. Read; Sean Mc Aullife - Aspetar**
Co-PI	**Mathew Wilson, Roald Bahr, Scott Gillogly, Rodney Whitely, Philippe Landreau**
IRB Application #	**F2017000227**
Site/s	**Aspetar**
Funding Entity	**Aspetar**
Protocol Title	**Factors associated with ACL injury, successful rehabilitation outcomes and return to sport following ACL reconstruction in athletic populations.**
Submission Type	**Ethics Approval Renewal**
Review Type	**Full Board**
Approval Period	**1st Nov, 2018 – 31st Oct, 2019**

The Anti-Doping Lab Qatar Institutional Review Board has reviewed and approved the above referenced protocol.
As the Principal Investigator of this research project, you are responsible for:

- Ethical compliance and protection of the rights, safety and welfare of human subjects involved in this research project.
- To follow the policies and procedures as set by ADLQ-IRB in any matters related to the project, following the ADLQ-IRB approval which includes:-
  - Obtaining prior approval of any modifications to the approved protocol including the change of research team members.
  - Reporting deviations and unanticipated events; major deviations within 24 hours.
  - Renewing Ethics annually or every six months if IRB requires it.
  - Submission of progress reports annually
  - Informing the ADLQ-RO of the date of commencement of the research.
- LPI may use the content of the approved Informed Consent form in their own organizational letter head, if it deems fit for the nature of the project.

ADLQ IRB ORS (Office of Research Support)
Ms. Noor Al Motawa

مختبر مكافحة المنشطات قطر
Anti Doping Lab Qatar

**For Commencement of Research, Protocol Deviation Reporting, Unanticipated Problem Reporting & Research Progress Annual Report, please contact - Education & Research Office, Anti-Doping Lab Qatar.*

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Lab Qatar

ADLQ RESEARCH OFFICE

P.O.BOX 27775
Email: ADLQ-RO@adlqatar.com

Date: 24/10/2018

Kindly inform if there had been any changes or deviations from the Protocol submitted and approved by previous Ethics Committee.