# Return to Sport Assessment and Decision Making Following Anterior Cruciate Ligament Reconstruction (ACLR) Surgery

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**Abstract**

The aim of this thesis was to explore return to sport (RTS) tests and criteria following anterior cruciate ligament reconstruction (ACLR) surgery, with a focus on both best-practice recommendations and real-world clinical outcomes. Despite the increasing use of RTS assessments to guide rehabilitation and reduce re-injury risk, substantial variability persists in test selection, performance thresholds, and their relationship to successful RTS. This research therefore sought to clarify what constitutes best-practice for RTS testing and to evaluate how these assessments perform in a clinical population.

This thesis comprises two complementary studies. Firstly, a scoping review synthesised the literature on RTS assessments and decision-making criteria following ACLR surgery in athletes. 33 studies were included and analysed according to test type, performance thresholds, and RTS definitions. Secondly, a retrospective descriptive analysis used clinical data from a physiotherapy clinic specialising in knee injury rehabilitation in Aotearoa New Zealand (NZ). RTS test outcomes were reported across strength, hop, jump, and psychological domains, and associations with demographic and clinical variables were examined.

The scoping review revealed marked heterogeneity in RTS testing, with little consensus on best-practice criteria. Most studies used strength and hop testing, with ≥90% limb symmetry index (LSI) as the primary threshold, but relatively few incorporated psychological or sport-specific measures. In the clinical cohort ($n$ = 165), RTS test pass rates were generally modest, and only a small proportion achieved over 90% LSI across all domains. Several clinical variables influenced performance; however, demographic and clinical factors showed limited association with RTS level. Whilst psychological readiness was significantly associated with RTS outcomes, higher physical RTS test scores did not consistently predict full return to pre-injury sport.

RTS testing following ACLR remains inconsistently defined and applied across both research and clinical settings. Although objective criteria are widely used to inform RTS decisions, the predictive value of current thresholds appears limited. These findings highlight the importance of developing more comprehensive, contextually informed RTS protocols that integrate physical, psychological, and sport-specific assessments. A multifactorial approach is recommended to optimise RTS decision-making and support improved long-term outcomes after ACLR.

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**Attestation of Authorship**

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning. Chapters 2 and 3 of this thesis represent two separate manuscripts that have been or will be submitted to peer-reviewed journals for consideration for publication. My contribution and the contribution of the co-authors to each of these papers are outlined at the beginning of this thesis. All co-authors have approved the inclusion of the joint work in this Master's thesis.

Alex Wright    Duncan Reid    Geoff Potts    Irene Zeng

**Candidate Contribution and Co-Authored Papers**

| | |
|---|---|
| **Chapter 2:** Return To Sport (RTS) Tests and Criteria Following an Anterior Cruciate Ligament (ACL) Reconstruction (ACLR): A Scoping Review | Wright 85%<br>Reid 10%<br>Potts 5% |
| **Chapter 3:** A Retrospective Descriptive Analysis of Return to Sport (RTS) Tests Following Anterior Cruciate Ligament Reconstruction (ACLR) Surgery | Wright 80%<br>Reid 7.5%<br>Potts 7.5%<br>Zheng 5% |

## List of Co-Authored Works Arising from The Master's Thesis

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**Ethical Approval**

Ethical approval for this research was granted by the Auckland University of Technology Ethics Committee (AUTEC). The AUTEC reference is 24/203, with approval granted on 15th August 2024 (Appendix A).

# Chapter 1: Introduction

## 1.1 Background

### 1.1.1 Anterior Cruciate Ligament Injuries in Sport

The anterior cruciate ligament (ACL) is one of two cruciate ligaments within the knee joint, playing a critical role in maintaining stability by resisting anterior translation of the tibia relative to the femur and contributing to rotational control (3). ACL injuries are among the most consequential musculoskeletal injuries in sport, often resulting in significant time loss, functional limitations, and long-term joint health implications (4, 5, 6). Epidemiological data indicates that injury rates have risen steadily in recent decades, with annual incidence estimates ranging from 30 to 78 per 100,000 person-years in some countries (7).

ACL injuries exist on a spectrum. Partial tears typically involve disruption of one bundle of the ligament (anteromedial or posterolateral) and may preserve some mechanical stability, while complete ruptures involve full-thickness disruption of the ligament, resulting in significant functional instability, particularly during pivoting and cutting movements (3). ACL ruptures are frequently accompanied by concomitant intra-articular damage such as meniscal tears, chondral lesions and bone bruising or impaction fractures of the femoral condyle and tibial plateau (8).

While ACL injuries can occur via contact mechanisms, such as a direct blow to the knee causing valgus collapse, the majority are sustained through non-contact mechanisms, including sudden deceleration, rapid change of direction (CoD), or landing from a jump with a relatively extended position (less then 30° flexion) and experiencing a valgus and internal rotation moment (3, 7, 9, 10). These injuries are common in athletes participating in sports that involve frequent cutting, pivoting, and landing movements such as football, rugby, netball, and basketball (4, 5, 6).

ACL injury mechanisms and situational patterns have been shown to vary markedly between sports, with four predominant categories: CoD, landing, direct contact, and gear-induced mechanisms, reflecting sport-specific demands and contexts (11). These injuries are increasing disproportionately in young athletes and females. In youth populations, rapid growth, delayed neuromuscular maturation, and challenges in movement control are believed to heighten vulnerability to high-risk mechanics during adolescent sport participation, contributing to elevated first-time injury and secondary injury rates following

ACLR (12, 13, 14). The increased participation of females in high-risk sports, combined with biomechanical (e.g., increased knee valgus moments), hormonal (e.g., oestrogen-mediated ligament laxity), and neuromuscular factors are also thought to contribute to this disparity (15).

### 1.1.2 Current Management of ACL Injury

The management of ACL injuries can broadly be classified into non-operative and operative pathways. For individuals seeking to return to high-risk sport, operative management is currently the most common pathway (16, 17, 18, 19).

Operative management typically involves an ACL reconstruction (ACLR). The goal of an ACLR is to restore mechanical stability to the knee by replacing the ruptured ligament with a graft. The graft serves as a scaffold that facilitates the process of ligamentisation, during which it undergoes biological remodelling and gradual transformation into tissue with structural and functional properties resembling the native ACL (20, 21). Common graft options include hamstring tendon (HT), bone-patellar tendon-bone (BPTB), and quadriceps tendon (QT) autografts, with the choice influenced by surgeon preference, patient characteristics, and sport-specific demands (22). The surgical procedure typically involves arthroscopic removal of the torn ligament remnants, preparation of bone tunnels in the femur and tibia, and graft fixation (23). Advances in surgical technique, such as anatomic tunnel placement, improved fixation methods, and double-bundle reconstruction, aim to better replicate native ACL biomechanics and potentially improve functional outcomes (24).

Despite advancements in surgical techniques and rehabilitation strategies, the outcomes following ACLR remain variable. While up to 80% of individuals have been reported to return to some level of sport following surgery (6), far fewer successfully regain their pre-injury performance levels. Return-to-performance rates are reported as low as 50%, with higher percentages represented by elite athletes (5, 25, 26, 27). Even among those who successfully RTS, the risk of sustaining a second ACL injury, either to the graft or contralateral knee, remains high. Re-injury rates as high as 24% have been reported globally (28), with repeat injury associated with significantly poorer long-term outcomes (29).

Whilst this thesis will focus on RTS following ACLR surgery, it is important to discuss the non-operative pathway. Non-operative management of ACL rupture aims to restore knee stability, function, and strength without reconstructive surgery. This approach is generally considered for individuals with partial or isolated tears, lower athletic demands, or those willing to modify activity levels (30, 31). Non-operative protocols have traditionally involved acute injury management and progressive rehabilitation focusing on quadriceps and hamstring strengthening, neuromuscular control, proprioceptive retraining, and sport-specific conditioning (32).

Recently, novel bracing approaches have emerged, such as the Cross Bracing Protocol (CBP) (33). This involves bracing the knee in 90 degrees of flexion immediately after injury and gradually restoring range of motion over several weeks to promote intrinsic healing by approximating the torn ACL ends. However, evidence remains preliminary and long-term outcomes are still unknown. Nevertheless, when successful, non-operative rehabilitation can allow patients to RTS or maintain an active lifestyle without the risks associated with surgery (30, 34).

### 1.1.3 Return to Sport Following ACLR Surgery

In response to the challenges involved in returning to sport following an ACLR, RTS decision-making has become a key focus in late-stage rehabilitation. RTS assessment protocols are designed to evaluate whether an athlete has regained sufficient physical capacity, functional performance, and psychological readiness to safely resume participation in sport. These assessments typically incorporate measures of lower limb strength, functional performance, movement quality, and psychological readiness questionnaires. These are summarised in Table 1.

*Table 1: Summary Table of RTS Test Domains and Test Examples*

| Domain | Test example | Description | Outcomes/Criteria |
|---|---|---|---|
| **Strength** | Isokinetic quadriceps/hamstring strength | Concentric/eccentric torque at set angular velocities (e.g., 60°/s, 180°/s, 300°/s) | Peak torque, Nm or kg(/body mass), LSI |

| | | | |
|---|---|---|---|
| | Isometric quadriceps/hamstring strength (MVIC) | Handheld/portable fixed dynamometry, typically at 60 or 90° knee flexion (quadriceps) and 90° (hamstrings) | Force (N or kg), LSI |
| | Unilateral leg press 1RM | Maximal unilateral press load with controlled form | 1RM load, LSI, bodyweight-normalised |
| **Hop** | Single hop for distance | Maximal forward hop with controlled landing | Distance, LSI |
| | Triple hop for distance | Three consecutive forward hops | Cumulative distance, LSI |
| | Crossover hop for distance | Three hops crossing a centre line | Distance, LSI |
| | Six-metre timed hop | Distance covered as fast as possible | Time, LSI |
| | Lateral hop | As many lateral hops as possible in 30s over a marker | LSI |
| **Jump** | Countermovement/vertical jump (bilateral or unilateral) | Vertical jump from standing, often on force plates | Jump height, RSI, asymmetry. |
| | Drop jump (bilateral or unilateral) | Step down from a box and jump vertically | RSI, contact time, jump height. |
| **Change of direction** | Running T-test | Pre-planned forward, lateral, and backward running. | Time, biomechanical asymmetry |
| **Agility** | Reactive agility test | Unplanned CoD in response to a stimulus | Time, errors, movement quality |

| | | | |
|---|---|---|---|
| **Psychological readiness** | ACL-RSI/IKDC/KOOS | Patient-reported outcomes for function, kinesiophobia, or QoL<br>Confidence, fear, and emotions relating to RTS | Composite score (e.g., out of 100) |

*Note: 1RM = One-Repetition Maximum, ACL-RSI = Anterior Cruciate Ligament-Return to Sport after Injury Scale, CoD = Change of Direction, IKDC = International Knee Documentation Committee, KOOS = Knee Injury and Osteoarthritis Outcome Score, LSI = Limb Symmetry Index, MVIC = Maximal Voluntary Isometric Contraction, N = Newton, Nm = Newton metre, QoL = Quality of Life, RSI = Reactive Strength Index, RTS = Return to Sport, °/s = Degrees per Second*

Strength testing for quadriceps and hamstrings are often performed using handheld and portable dynamometry to measure a maximal voluntary isometric contraction (MVIC), or isokinetic dynamometry at varying angular velocities to measure peak torque of knee extension and flexion (35, 36, 37).

Isokinetic testing enables detailed torque-angle and torque-velocity profiling and is often regarded as the gold standard for quantifying quadriceps and hamstring function (38). Testing is typically performed in a seated position with the hip flexed at 90°, and the dynamometer records force output through controlled ranges of motion. Results are reported as absolute torque (Nm), torque normalised to bodyweight (Nm/kg), or as a limb symmetry index (LSI). However, access to such equipment is limited in many clinical environments due to cost and availability (39). Handheld and portable dynamometry offers a more clinically accessible alternative. Using a “make” test, patients perform a MVIC usually at 60° or 90° of knee flexion for quadriceps and 90° for hamstrings, with outputs again expressed relative to body mass or as an LSI (40).

In some clinical and rehabilitation settings, unilateral incline leg press one-repetition maximum (1RM) testing is also employed, where load is progressively increased until the athlete can no longer complete a repetition with controlled form (i.e. without compensatory trunk or hip movement) (41, 42). This measure captures closed-chain force production and integrates contributions across multiple joints, and results can be expressed either as LSI between limbs, load (kg) or load normalised to body mass (kg/BM). Whilst providing a familiar and accessible assessment tool for athletes, unilateral incline leg press 1RM allows clinicians to capture contributions from hip musculature as well as the quadriceps (41, 42).

Functional performance is commonly assessed using single leg hop tests, with some protocols incorporating vertical jumps or reactive jump assessments to evaluate performance asymmetries (4, 6, 43). The single leg hop for distance involves a maximal forward hop from a standing start, landing on the same limb with controlled balance maintained for two to three seconds. The triple hop repeats this movement three times consecutively, capturing both power and endurance qualities. The crossover hop requires three consecutive hops while alternately crossing a central line, challenging mediolateral stability and coordination. The six-metre timed hop involves covering the distance as quickly as possible, providing a measure of speed.

Jump tests, such as the countermovement jump (CMJ), single leg vertical jump (VJ) or drop jump (DJ; bilateral or unilateral) are used to evaluate vertical power, landing strategies, and reactive strength capabilities, typically using force plates. In more advanced clinical and research settings, three-dimensional (3D) motion capture and force plate analysis are used to detect interlimb biomechanical differences and compensatory movement patterns (44).

Finally, psychological readiness is often assessed using validated patient-reported outcome measures (PROMS) that evaluate confidence, emotions, and risk appraisal in relation to sport participation by quantifying constructs such as fear of reinjury, perceived knee function, motivation, and confidence in performance (20, 45). These measures acknowledge that RTS is not solely a biomechanical milestone but also a psychological transition, requiring the athlete to tolerate uncertainty, re-engage with high-risk movements, and re-establish trust in the surgical knee.

Achieving objective RTS criteria in a test battery, often defined as equal to or over 90% LSI for strength, hop and jump tests, alongside satisfactory psychological readiness scores, has been associated with reduced risk of graft rupture and contralateral injury (4, 6, 46).

However, ongoing debate surrounds the ecological validity of current RTS assessment. For instance, LSI-based benchmarks have been criticised for overestimating readiness, as they compare the injured limb to a contralateral limb that may also be deconditioned (47). Moreover, persistent quadriceps deficits following ACLR may reflect not only true strength loss but also an underlying neuromuscular mechanism known as arthrogenic muscle inhibition (AMI). AMI arises from altered afferent input from the injured knee joint, resulting in reduced voluntary quadriceps activation despite adequate muscle mass (48). This inhibitory mechanism may partly explain why some individuals continue to demonstrate reduced quadriceps symmetry even after prolonged rehabilitation and structured strengthening programmes.

Nevertheless, restoration of voluntary activation and interlimb symmetry does not necessarily equate to restoration of dynamic neuromuscular control during sport-specific tasks. Evidence suggests that athletes may achieve traditional hop and strength symmetry thresholds yet continue to exhibit aberrant biomechanics, particularly during cutting manoeuvres or reactive decision-making tasks (49, 50). Therefore, traditional RTS tests may fail to capture higher level movement coordination demands required in sport, highlighting the limitations of pre-planned, symmetry-based RTS criteria when used in isolation.

Additionally, non-contact ACL injuries typically occur during high-speed deceleration, cutting, or landing, and video-based analyses demonstrate that injury events unfold rapidly after initial foot contact (51). This suggests a potential mismatch between the rapid timescale of injury and the slower, controlled nature of common RTS tests.

Emerging evidence also demonstrates that RTS outcomes may be influenced by deficits in perceptual-cognitive and skill-acquisition processes (50, 52). Athletes who demonstrate poorer ability to interpret environmental cues, anticipate opponent movement, or adapt to unplanned stimuli exhibit altered knee loading and high-risk mechanics during cutting tasks (49, 53, 54). Neurocognitive challenges, such as dual-task demands, reaction-time constraints, or rapid decision-making, have been shown to reduce hop performance and increase asymmetry despite athletes passing traditional RTS tests (52, 55, 56).

Collectively, these findings suggest that common RTS batteries focused solely on strength symmetry and pre-planned tasks may overlook critical cognitive and environmental demands that influence reinjury risk and sport performance following ACLR surgery. In response to these limitations, several authors have advocated for the integration of more comprehensive strength, neuromechanical, and neurocognitive assessments within RTS frameworks. This includes the use of alternative strength benchmarks, such as pre-injury baselines or bodyweight-adjusted thresholds (46, 47, 48), as well as reactive agility tasks, unanticipated CoD drills, and neurocognitive-challenged hopping tasks (49, 50). These approaches aim to better simulate the perceptual, temporal, and motor demands inherent in sport.

Overall, these insights highlight why expanding RTS test batteries beyond traditional strength and hop metrics is increasingly advocated, and they underscore the need for research to evaluate real-world RTS outcomes and testing performance within clinical practice.

#### 1.1.4 Integrated Care Pathways in Aotearoa NZ

In Aotearoa New Zealand (NZ), care pathways for ACL injuries have evolved considerably in recent years through initiatives aimed at improving consistency and patient outcomes (57, 58, 59, 60). The management of ACL injuries occurs within a unique healthcare framework shaped by the Accident Compensation Corporation (ACC), a national, no-fault injury insurance scheme that funds treatment for injuries caused by accidents (35, 61). As nearly all ACL ruptures are classified as accident-related, ACC typically covers the full cost of surgical reconstruction for those who elect to undergo surgery and subsidises rehabilitation services, such as physiotherapy, for injuries sustained through sport or other activities (59). While ACC has long contributed toward rehabilitation costs (57), patients are typically responsible for clinic co-payments, and subsidies are often time limited (59).

In recent years, new integrated care pathways (ICP's) have emerged to improve outcomes, standardise care, and reduce financial barriers to rehabilitation (58). Within the ICP Musculoskeletal (ICPMSK) pathway funded by ACC, one example of a consortia with a contract to deliver services is Careway. This consortia has developed a collaborative model of care to streamline and standardise ACL care across surgical and rehabilitation phases (62). Unlike standard ACC coverage, pathways like Careway fund the full cost of approved rehabilitation, including all clinic co-payments, and extends the duration of funded rehabilitation services. Careway also offers additional supports such as gym membership subsidies, enabling access to rehabilitation facilities, and taxi subsidies to assist patients with mobility or transport limitations.

Such pathways provide structured, evidence-informed guidelines for rehabilitation progression and standardised assessment (63). Within Careway, RTS decision-making incorporates objective strength testing (e.g., isokinetic or portable dynamometry), functional hop and jump performance, and psychological readiness measures. The inclusion of these domains reflects alignment with widely accepted RTS frameworks, which emphasise quantifiable physical capacity alongside patient-reported confidence as central components of RTS assessment (6, 16).

Strength, jump and hop tests were adopted because they offer reproducible, scalable metrics of neuromuscular recovery that can be benchmarked against defined thresholds. In applied settings, these measures provide clinicians with objective indicators of interlimb asymmetry, residual quadriceps deficits, and global lower-limb function, supporting transparent progression decisions across rehabilitation phases. Hop and jump assessments have historically been viewed as approximations of sport-specific physical demands, as they challenge single-leg force production and dynamic stability, qualities relevant to high-speed deceleration, cutting, and landing mechanics (3, 7, 9, 10). Their integration within Careway therefore reflects an effort to operationalise evidence-based RTS constructs within a pragmatic, nationally coordinated model of care (4, 6, 43).

By establishing a nationwide framework and addressing common financial and logistical barriers, integrated care pathways may represent an important step toward improving equitable access to structured ACL rehabilitation in Aotearoa NZ. Early implementation suggests improvements in communication between providers and greater visibility of RTS testing outcomes at a population level (60, 64), although ongoing evaluation is required to determine its sustained impact on long-term RTS outcomes.

### 1.2 Rationale and Significance of the Research

Given the complexity of ACL rehabilitation and the substantial risk of re-injury following RTS, there is a critical need for more consistent, evidence-based approaches to pre- and post-operative rehabilitation and RTS assessment. Current literature shows wide variability in test batteries, pass thresholds, and definitions of readiness, making it difficult to compare outcomes across studies or to develop clinical best practice guidelines (1). Furthermore, while many RTS protocols focus on functional recovery, there is increasing recognition that psychological, contextual, and sport-specific factors are equally important in determining safe and successful return.

The rationale for this thesis stems from the need to consolidate existing evidence and explore how RTS testing is implemented in real-world clinical settings. While previous reviews have mostly examined isolated aspects of RTS testing, few have comprehensively analysed RTS assessment in broad, clinical cohorts post-ACLR. Moreover, there is a lack of research describing how these assessments are applied in practice, how athletes perform across multiple test domains, and which clinical or demographic factors may influence outcomes.

## 1.3 Aim and Research Questions

### 1.3.1 Aim

The overarching aim of this thesis is to examine the application, outcomes, and current best practice surrounding RTS testing following ACLR surgery. By combining a scoping review with a retrospective analysis of real-world clinical data, this research seeks to enhance our understanding of how RTS testing is defined, implemented, and interpreted both in the literature and in clinical practice. The ultimate goal is to inform more robust, evidence-based, and contextually relevant decision-making protocols for athletes recovering from ACLR surgery.

### 1.3.2 Research Questions

1. What is the current best practice for RTS testing?
2. What is the overall pass rate for RTS testing after ACLR?
3. At what average time point post-surgery do individuals typically pass RTS testing after ACLR?
4. Are RTS test scores associated with age, gender, ethnicity, time from surgery, sport type, or graft type?
5. What proportion of athletes who pass RTS tests achieve >95% limb symmetry?
6. Do individuals who achieve >95% limb symmetry have higher rates of return to pre-injury level of sport performance?

### 1.4 Thesis Structure

This thesis adopts a manuscript structure and is divided into two main research chapters, each representing a standalone manuscript submitted to a peer-reviewed journal (Figure 1). As such, each chapter includes its own abstract, introduction, methods, results, discussion, and conclusion sections. This structure is consistent with the goal of producing publishable outputs but also results in some necessary repetition of content, particularly in relation to the background and justification for the research.

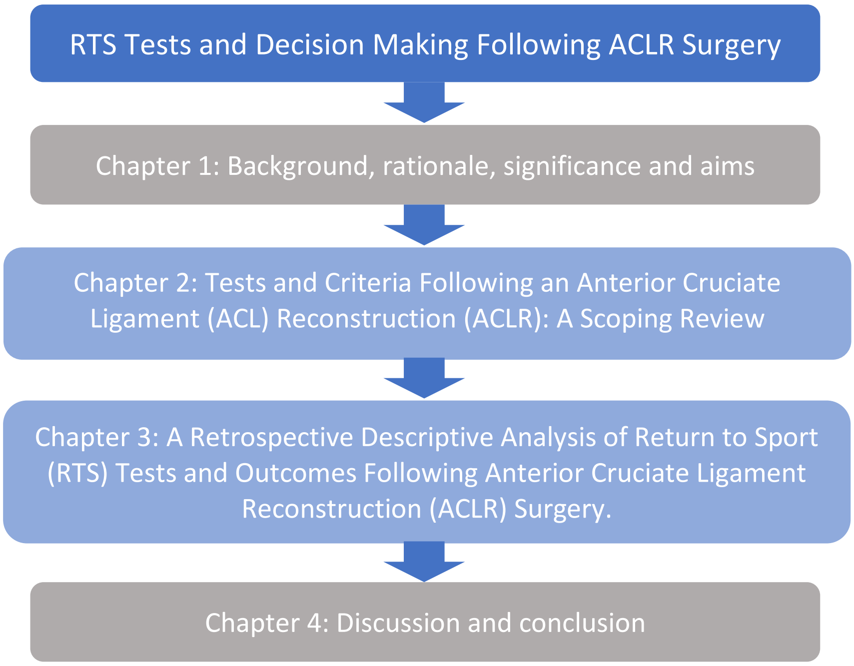


*Figure 1: Thesis Structure*

Chapter 2 presents a scoping review of RTS tests and decision-making criteria used in the literature following ACLR. The review identifies common tests and thresholds, summarises trends across studies, and highlights areas of inconsistency and gaps in evidence. Chapter 3 presents a retrospective descriptive analysis of RTS assessments and RTS outcomes in a clinical cohort from a specialised physiotherapy clinic in Aotearoa NZ. This study describes test performance across multiple domains, explores associations with demographic and clinical factors, and investigates whether high RTS test performance is associated with improved RTS outcomes. The final chapter synthesises the findings from both studies, discusses their implications for clinical practice, and provides recommendations for future research and implementation.

**Prelude to Chapter 2**

This chapter presents a scoping review of RTS tests and decision-making criteria following ACLR, with a focus on athletes returning to pivoting sport. The review uses a structured methodology to identify and synthesise data from 33 studies, providing an overview of commonly used RTS assessments, performance thresholds, and study characteristics.

Findings from this review reveal considerable heterogeneity in RTS testing protocols, limited use of sport-specific or neurocognitive assessments, and inconsistent application of psychological readiness measures. The review identifies key gaps in current practice and supports the need for more comprehensive and standardised RTS criteria.

This chapter has been formatted as a standalone manuscript intended for submission to The Knee, a peer-reviewed journal. While some overlap with other sections of the thesis may occur, this is consistent with the thesis' manuscript structure.

# Chapter 2: Return To Sport (RTS) Tests and Criteria Following an Anterior Cruciate Ligament (ACL) Reconstruction (ACLR): A Scoping Review

## 2.1 Abstract

ACLR surgery is a common procedure to restore knee stability and enable athletes to RTS. This scoping review aimed to explore RTS tests and criteria used in decision-making following ACLR surgery. A scoping review methodology was undertaken. A comprehensive search of MEDLINE, CINAHL, and SPORTDiscus was conducted to identify studies reporting RTS tests and criteria for athletes post-ACLR. Studies involving level I and II sports were included. Data was extracted and study characteristics, RTS criteria, and results were summarised.  Of 1,703 studies screened, 33 met the inclusion criteria, involving over 6,000 participants. RTS criteria showed significant variability across studies, with protocols emphasising limb symmetry indexes (LSI) for strength and jump and hop performance, often set at ≥90%. RTS timing ranged from a minimum of six to nine months post-surgery. While psychological readiness was frequently reported, assessments of change of direction, agility, and biomechanics were less common. This review highlights the lack of standardisation in RTS protocols, leading to inconsistencies in clinical practice. Developing consistent, evidence-based guidelines is essential to

enhance RTS outcomes, minimise re-injury risk, and optimise performance for athletes post-ACLR.

### 2.2 Highlights

1. RTS testing methods showed variability across studies and sport levels, although strength, jump and hop performance, and physiological readiness is often assessed
2. Few studies focused on professional athletes, most included amateur participants
3. Standardised RTS protocols are essential to enhance outcomes and reduce re-injury risk
4. Sport-specific assessment, including change of direction, agility, and neurocognitive tasks, are often overlooked

### 2.3 Introduction

ACL injuries are common in sport and have deleterious effects for athletes (4, 25, 65). ACL injury rates are increasing, particularly in females and younger athletes (18), with an annual incidence ranging from 30 to 78 per 100,000 person-years in the United States (7). Most ACL injuries occur during non-contact pivoting and cutting manoeuvres in sports such as football, netball, basketball, and rugby (18, 19). While non-operative management is an option, the prevailing choice for those aiming to resume sport is undergoing an ACLR, considered by many as the gold standard treatment (16, 17).

While nearly 80% of individuals are reported to RTS following an ACLR (66), many do not reach pre-injury performance levels (5, 25, 26). Return to pre-injury performance rates range from 50% to 90%, with elite athletes representing the higher percentages (27). RTS following an ACLR also carries a significant risk of graft or contralateral ACL rupture (67, 68), often leading to poorer outcomes (29). Global rates of ACL graft rupture can reach up to 24% (28). Rehabilitation must focus on identifying those at greater risk of a second injury and restoring pre-injury performance levels.

While passing RTS criteria has shown promise in reducing ACL re-injury rates (4, 6, 46), the lack of standardised criteria for RTS assessment remains a challenge (69). Despite the growing popularity of criterion based RTS decision-making, a consensus on tests and pass thresholds remains elusive, leading to high variability in definitions, evaluations, and reporting (70). Correspondingly, published literature reflects significant heterogeneity in

RTS pass rates, ranging from 18.8% to 88.1% (71). This scoping review aims to assess the tests and criteria currently used to support RTS decision-making following ACLR.

**2.4 Methods**

A scoping review was selected due to the broad scope of the research question and the wider inclusion criteria compared to a traditional systematic review. Scoping reviews offer the advantage of summarising and disseminating research findings while also identifying gaps in the existing literature. This review follows the five-stage methodological framework outlined by Arksey and O'Malley (72), with additional guidance from the Joanna Briggs Institute (JBI) Reviewer Manual (73, 74). To ensure transparency and rigor, the review was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews (PRISMA) and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) which is detailed in Figure 2.

The initial step was to identify the research question, centred on how specific tests or criteria influence RTS decision-making following ACLR surgery. The JBI recommends using the PCC (Population, Concept, and Context) framework for scoping reviews as it provides a structured approach for formulating clear and meaningful objectives and eligibility criteria (75). The primary aim was to ascertain which tests or criteria (concept) are reported and utilised in RTS decision-making (context) for athletes post-ACLR (population).

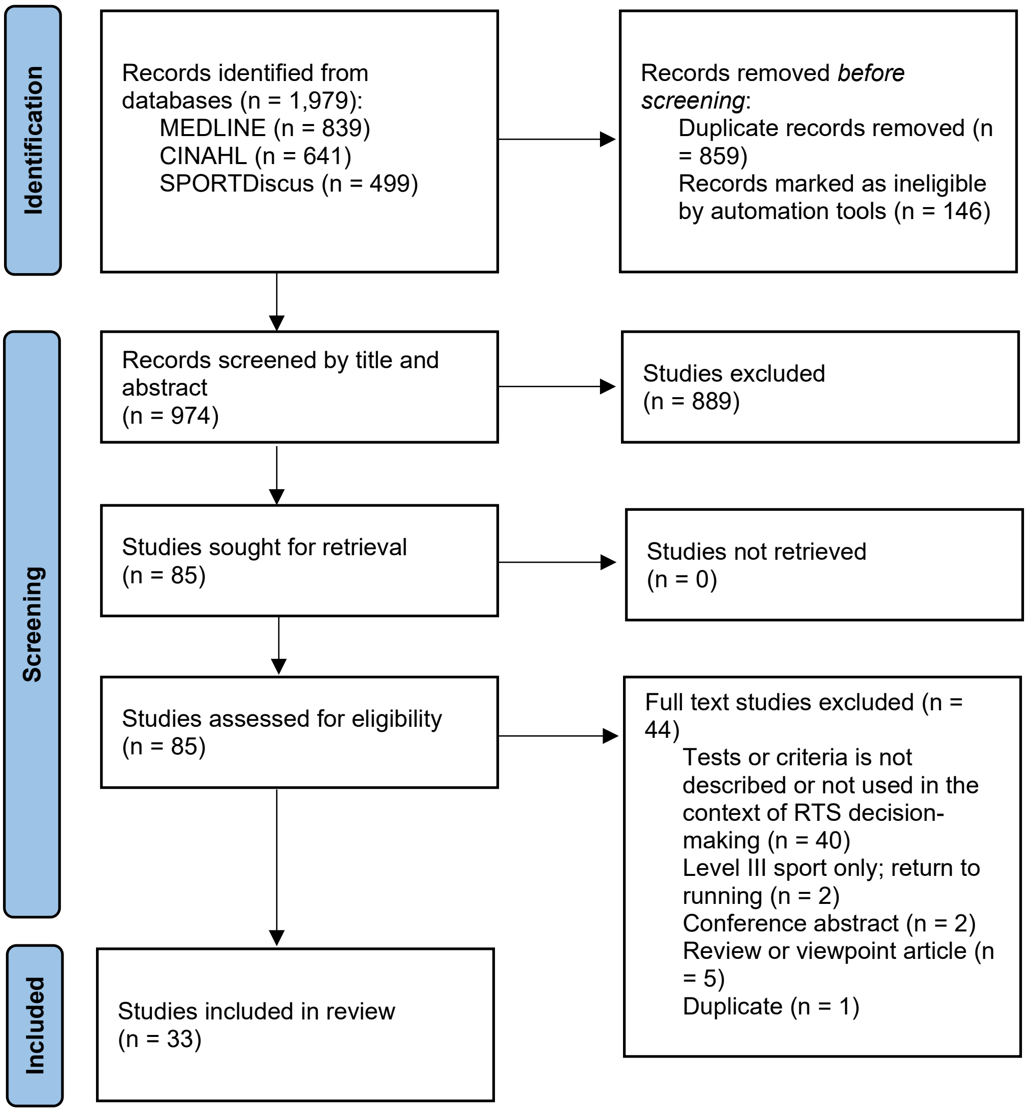


*Figure 2: Preferred Reporting Items for Systematic Reviews (PRISMA) and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) Diagram*

In the second step, relevant studies were identified through a structured search strategy using the search terms listed in Table 2. This search utilised Medical Subject Headings (MeSH) terms in the title and abstract across three key databases: MEDLINE, CINAHL, and SPORTDiscus. Automation techniques were employed to filter results to peer-reviewed academic journals, and duplicates were removed, yielding 775 studies for screening. This comprehensive search strategy ensured a thorough identification of relevant literature on the topic.

*Table 2: Scoping Review Search 22/07/2024*

| Search terms | Records identified |
|---|---|
| **XB** "Anterior cruciate ligament reconstruction” **OR** “ACL reconstruction” **OR** ACLR | MEDLINE (n = 14,858)<br>CINAHL (n = 9,375)<br>SPORTDiscus (n = 6,725) |
| **AND** "Return to play" **OR** "return to sport" **OR** “return to competition” | MEDLINE (n = 1,497)<br>CINAHL (n = 971)<br>SPORTDiscus (n = 763) |
| **AND** test* or criteria | MEDLINE (n = 839)<br>CINAHL (n = 641)<br>SPORTDiscus (n = 499) |

The third step involved the selection of studies based on the inclusion and exclusion criteria detailed in Table 3. Only peer-reviewed interventional or observational studies with more than 10 participants were included. These focused only on ACLR surgery in athletes participating in level I (frequent cutting, pivoting, and abrupt changes in direction) or II sport (occasional quick changes in direction), defined by the Cincinnati Sports Activity Scale (CSAS) (76). For studies that did not report the athletes’ sport level, participation at a minimum of level II was assumed if RTS occurred six months post-ACLR, and RTS testing included strength or jump performance with a limb symmetry index (LSI) pass threshold of 80% or higher. Studies relating to surgical techniques, graft choices, or those that did not specify RTS criteria were excluded. This screening process resulted in a subset of studies directly relevant to RTS decision-making post-ACLR (n = 33).

Screening of titles, abstracts, and full texts was conducted by a single reviewer (AW), consistent with accepted scoping review methodology outlined by JBI and Arksey & O’Malley (72, 73, 74). While dual-reviewer screening is desirable, it is not a mandatory requirement for scoping reviews, which aim to map the breadth of available evidence rather than formally evaluate study quality or risk of bias. The use of a single reviewer introduces the potential for selection bias, although this risk was minimised through adherence to a pre-specified screening protocol, consistent application of eligibility criteria, and consultation with supervisors when uncertainties arose.

*Table 3: Inclusion and Exclusion Criteria*

| **Inclusion** | **Exclusion** |
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| Study design: peer-reviewed interventional or observational study with >10 participants and clinical practice guidelines or recommendations | Study design: systematic reviews, conference abstracts, surveys, case reports, case series, translations, non-peer reviewed interventional or observational studies, study protocols |
| Participants: human, participating in level I or II sport, primary ACLR, revision ACLR | Participants: non-human (animal or cadaver), non-op ACL, ACL repair, not ACL-related, not participating in sport or participating in level III sport |
| Outcome: describes specific test or criterion used for RTS decision-making (e.g. reported scales, strength, jump performance) | Outcome: surgical techniques or graft choice, no description of specific test or criterion used to inform RTS decision-making following an ACLR, or testing or criteria is not described in the context of RTS decision-making |

In the fourth step, key details from the selected studies were extracted and summarised in Table 4. This data extraction included information on study design, participant characteristics, and the specific tests or criteria used for RTS decision-making. The standardised format for data extraction ensured consistency and comparability across the included studies, aligning with the review's objectives. The key themes derived from this synthesis are presented in Table 4, offering valuable insights into the current landscape of RTS decision-making which will be discussed in the sections to follow.

*Table 4: PCC Framework Data Extraction*

| **Author (year)** Study type | **Objective** | **Population** | **Concept (RTS test/criteria)** | **Context (Sport type)** | **Other outcomes** | **Results** |
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| **Angelozzi, Madama (77)** Descriptive, prospective, longitudinal single cohort study | To investigate the RFD of MVIC as an outcome measure for determining readiness for RTS | 45 male professional footballers<br>Mean age (SD): 23.4 (4.7)<br>Graft type: HT autograft | IKDC, laxity, isometric leg press MVIC and RFD | I | Tegner score | - Average MVIC at 6m post-op was 97%<br>- Average RFD at 6m post-op was 80% ($RFD_{30}$), 77% ($RFD_{50}$), and 63% ($RFD_{90}$)<br>- Mean RFD >90% was achieved at 12m post-op |
| **Di Stasi, Logerstedt (78)** Controlled laboratory study | To compare gait characteristics of athletes who pass and do not pass RTS criteria 6m post-ACLR | 42 athletes<br>30 male, 12 female<br>Mean age (SD): 29.3 (10.8)<br>Graft type: soft tissue allograft or HT autograft (n=NR) | Isometric knee extension strength, SHD, THD, CHD, 6MTH, KOS-ADLS, GRS | I | KFAIC, KFAPKF, KEMPKF | - Athletes who do not pass RTS criteria demonstrate significant differences between limbs in all kinematic and kinetic variables at the knee (*p*≤0.27) |

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| **Gardinier, Di Stasi (79)** Descriptive laboratory study | To determine whether knee joint contact force asymmetries during gait exist 6m post-ACLR and whether these are associated with performance on RTS tests | 29 patients 17 male, 12 female Mean age (SD): 29.15 (10.75) Graft type: HT autograft (12) or allograft (17) | KOS-ADLS, GRS, isometric knee extension strength, SHD, THD, CHD, 6MTH | I, II | MCpk, TCpk | - No significant or meaningful differences in joint or muscle contact forces among all patients<br>- Those who failed RTS testing exhibited meaningful contact force asymmetries with tibiofemoral contact force being significantly lower in the involved limb |
| **Müller, Krüger-Franke (80)** Prospective cohort study | To find predictive parameters for successful RTS post-ACLR | 40 patients 21 male, 19 female Mean age (SD): 32.2 (10.4) Graft type: HT autograft | Isometric knee extension and flexion strength, SHD, THD, CHD, square hop test, IKDC, TSK-11, ACL-RSI, | I, II (38), III (8) | | - No difference between RTS and non-RTS patients with strength, square hop and TSK-11.<br>- LSI for single hop for distance, crossover, and triple hop, and ACL-RSI and IKDC were significantly lower in non-RTS patients |

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| **Grindem, Snyder-Mackler (4)** Observational cohort study | To assess the relationship between reinjury post-ACLR and return to level I sport, timing for RTS and knee function before RTS | 100 patients 46 male, 54 female Mean age (SD): 24.3 (7.3) Graft type: HT or PT autograft (n=NR) | Isokinetic knee extension strength, SHD, CHD, THD, 6MTH, GRS | I | - Patients who returned to level I sport had a 4.32x (*p*=0.048) higher rate of injury<br>- Reinjury rates reduced by 51% for each month RTS was delayed until 9 months post-ACLR<br>- 38.2% who failed RTS testing reinjured vs 5.6% who passed<br>- More symmetrical knee extension strength significantly reduced reinjury rates |
| **Kyritsis, Bahr (46)** Observational cohort study | To evaluate whether objective discharge criteria are associated with risk of ACL graft rupture after RTS post-ACLR | 158 male professional athletes Mean age (SD): 21.5 (4.5) Graft type: HT or PT autograft (n=NR) | Isokinetic knee extension and flexion strength, running t-test, SHD, THD, CHD | I | - 16.5% sustained an ACL graft rupture (average=105 days post-RTS)<br>- Not meeting all discharge criteria (RTS tests) and decreased H:Q ratio (at 60d/s) were associated with increased risk of ACL graft rupture |
| **Gokeler, Welling (81)** | To develop a test battery to ensure | 28 patients 22 male, 6 female | Isokinetic knee extension and flexion strength, | I, II | At 6m post-ACLR:<br>- 2 patients passed RTS test battery<br>- 67.9% passed LESS |

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| Observational cohort study | safe RTS post-ACLR | Mean age (SD): 25.5 (8.3)<br>Graft type: NR | H:Q ratio, jump-landing task assessed with LESS, SHD, THD, SH, ACL-RSI, IKDC | | | - 78.5% passed SHD<br>- 85.7% passed THD<br>- 50% passed SH<br>- 39.3%, 46.4% and 42.9% passed knee extension peak torque at 60, 180 and 300°/s respectively<br>- 85.7% passed IKDC<br>- 75% passed ACL-RSI |
| **Wellsandt, Failla (47)**<br>Prospective cohort study | To evaluate the use of the unaffected limb as a reference standard for LSI in RTS testing and its relationship with second injury | 70 athletes<br>47 male, 23 female<br>Mean age (SD): 26.6 (10)<br>Graft type: NR | Isometric knee extension strength, SHD, CHD, THD, 6MTH, IKDC, GRS | I | EPIC levels | - 57.1% passed RTS tests but only 28.6% met 90% EPIC levels<br>- EPIC levels were more sensitive than LSIs in predicting second ACL injury (LSI, 0.273; 95% CI: 0.010, 0.566; EPIC, 0.818; 95% CI: 0.523, 0.949) |
| **Burland, Kostyun (82)**<br>Cross-sectional study | To investigate the relationship between self-reported and functional outcome | 50 athletes<br>27 male, 23 female<br>Mean age (SD): 15.9 (1.82) | Isometric and isokinetic knee extension and flexion strength, pedi-IKDC, ACL-RSI | NR | | - ↑ strength was associated with ↑ ACL-RSI and pedi-IKDC scores<br>- Differences were found in isometric extension strength (*p*=.001) and isokinetic extension strength at 180°/s |

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| | measures on RTS timing in adolescent athletes identify a cut-off value for knee extension strength | Graft type: HT autograft | | | | ($p$=.03) and 300°/s ($p$=.002) between those who RTS and those who did not<br>- A 6-month isometric extension deficit (mean LSI = 85.48 ± 23.15) accurately identified patients who RTS after ACLR (AUC=0.82, 95% CI=0.68, 0.95) |
| **Ebert, Edwards (83)** Prospective cohort study | To compare the 'Back in Action' (BIA) test battery to standard RTS criteria (hop and strength test) | 40 participants 25 male, 15 female Mean age: 23.8 Graft type: HT autograft | Isokinetic knee extension and flexion strength, 6MTH, SHD, THD, CHD, | I, II | BIA test battery | - Significantly less participants passed the BIA compared with the standard RTS test batteries ($p$<0.001)<br>- LSIs for the standard hop test battery were significantly ↑ than the BIA single leg tests ($p$<0.001) |
| **O'Malley, Richter (84)** Cross-sectional study | To examine CMJ and isokinetic strength to identify which measures can distinguish between ACLR and control | 118 male athletes Age: 24-26 Graft type: PT autograft | isokinetic knee extension and flexion strength, SL CMJ, | I | | - The CG differed strongly from ALCR group in isokinetic knee extension peak torque ($d$=-1.33), SL CMJ performance ($d$>0.4) and LSI in isokinetic strength and jump outcomes ($d$>1.1) |

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| | participants and provide normative values for young male field athletes | | | | | |
| **Webster and Feller (85)** Observational cohort study | To determine the proportion of athletes who return to level I sport within 12m, compare return rates by age and sex and examine whether RTS is associated with some commonly used outcome criteria | 1440 athletes 992 male, 448 female Mean age (SD) = 26 Graft type: HT autograft (1414), PT autograft (8), LARS (18) | SHD, knee laxity (arthrometer), IKDC | I | Number of athletes who RTS within 12m | - RTS was ↑ in athletes aged ≤25 (48%) than those aged 26-35 ($p$<.0001) or 36+ ($p$<.001)<br>- Males had ↑ return rates than females in the ≤25 (52% vs 39%) and 26-35 (37% vs 18%) groups, with no sex differences >36<br>- Younger athletes were more likely to meet RTS criteria<br>- Athletes with an LSI ≥90 were 2x as likely to RTS ($p$<.0001), and those with IKDC scores ≥95 were 3x as likely to RTS ($p$<.0001) |
| **Welling, Benjaminse (86)** | To assess changes over time in patients tested at 6 and 9 months | 64 patients 45 male, 17 female Mean age = 24.2 | Isokinetic knee extension and flexion strength, jump-landing task assessed | I, II | | - At 6m, 3.2% passed all criteria, increasing to 11.3% at 9m<br>- Patients improved in all RTS criteria over time, except for IKDC |

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| Prospective, longitudinal, cohort study | post-ACLR using a RTS test battery | Graft type: HT autograft (45), PT autograft (19) | with LESS, SHD, THD, SH, IKDC, ACL–RSI | | | - At 9m, 46.8% failed the strength criterion at 60°/s |
| **Barfod, Feller (87)**<br>Prospective cohort study | To examine the association between knee extensor strength and hop distance and evaluated strength deficits at 6m and 12m post-ACLR | 69 patients<br>47 male, 22 female<br>Mean age (SD) = 27.1 (8.1)<br>Graft type: HT autograft | Isokinetic knee extension strength, SHD | NR | | - At 6m, 27.5% of patients had satisfactory knee extensor strength, increasing to 46.4% at 12m<br>- 66.7% achieved hop symmetry at 6m and 89.9% at 12m<br>- Hop distance recovery was not linked to knee extensor strength |
| **Lloyd, Oliver (88)**<br>Cross-sectional study | To examine the discriminative ability of LSI threshold 90% using total hop distance vs reactive strength ratios of individual | 20 male footballers<br>Mean age (SD) = 24.6 (4.2)<br>Graft type: HT autograft (16), PT autograft (4) | THD | I | Contact time, flight time, RSR | - Significant, small to moderate between-limb differences (*p*<0.05) for triple hop distance, flight time and RSR for each hop, with lower performance consistently displayed in the operated limb |

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| | hops during a triple hop test | | | | - Large, significant differences in RSR between hops one and two on the operated limb ($p<0.05$)<br>- 80% of participants achieving 90% LSI for total hop distance<br>- <50% of participants reached the 90% LSI threshold for RSR |
| **Sugimoto, Heyworth (14)**<br>Cross-sectional study | To examine the proportion of skeletally immature, paediatric ACLR patients who achieve ≥90% on RTS tests | 105 young patients<br>62 male, 43 female<br>Mean age (SD) = 13.4 (1.4)<br>Graft type: HT autograft (54), ITB autograft (51) | Isometric knee extension, knee flexion, hip abduction and hip extension strength, YBT, SHD, THD, CHD, 6MTH | NR | - Only 4.2% patients demonstrated ≥90% LSI in all RTS tests<br>- % of patients who passed all 4 strength, 3 balance, and 4 hop tests were 20, 65.4, and 27.8% respectively |

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| **Webster and Feller (68)** Prospective, logitudinal, cohort study | To determine the proportion of patients who pass RTS tests 6m post-ACLR; age, sex, and activity level differences between those who pass and do not pass; and specific tests are associated with return to competitive sport at 12m | 450 patients<br>274 male, 176 female<br>Mean age (SD) = 24 (7)<br>Graft type: HT autograft (391), QT autograft (47), PT autograft (12) | Isokinetic knee extension strength, IKDC, ACL-RSI, SHD, CHD | I (381), II/III (69) | - 3.8% met all 5 test criteria at 6m and 21% did not pass any test<br>- More of the younger patients (<21 years) passed all functional tests ($p$<.01)<br>- More male patients met the IKDC threshold (P = 0.03)<br>- Patients who played level I sports had the same pass rates as those who played level II/III sports<br>- Patients who passed the thresholds for the ACL-RSI and IKDC had 4x and 3x the odds of RTS at 12 months, respectively ($p$<.0001)<br>- ≥90% LSI for quadriceps strength or either hop test at 6m was not associated with RTS |
| **Welling, Benjaminse (89)** Prospective cohort study | To compare the results of a RTS test battery between patients who RTS (pre-injury level) and | 64 patients<br>44 male, 20 female<br>Mean age (SD) = 27.8 (8.8) | Isokinetic knee extension and flexion strength, jump-landing task assessed | I | - Significantly ↓ LESS score in RTS group ($p$=0.01)<br>- Significantly ↑ absolute scores on hop tests with both legs in RTS group |

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| | patients who did not RTS | Graft type: HT autograft (45), PT autograft (19) | with LESS, SHD, THD, SH | | - Significantly ↑ hamstring strength in the injured leg in RTS group (*p*=0.009 at 60°/s; 0.012 at 180°/s; 0.013 at 300°/s)<br>- No differences in test results were identified between patients who sustained a second ACL injury and patients who did not |
| **Franck, Saithna (90)**<br>Case control study | To determine the key factors that influence RTS test scores, when using K-STARTS (a composite score) | 676 patients<br>Casual to professional sport participation<br>476 male, 200 female<br>Mean age (SD) = 27.6 (10.4)<br>Graft type: HT autograft (624) or PT autograft (52) | ACL-RSI, QASLS, SHD, THD, CHD, SH, MICODT | NR | - Significantly ↑ K-STARTS score in males ($p<0.001$), younger patients ($p<0.001$) patients with hamstring graft vs patella tendon graft ($p=0.003$) and in patients who completed specific RTS programme ($p<0.001$)<br>- Completion of specific RTS programme only factor that influenced K-STARTS score beyond minimal detectable change |

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| **Higbie, Kleihege (91)** Retrospective cohort study | To compare self-reported and functional test performance, and re-injury rates in patients with high (≥33%) versus low (<33% ) isometric hip abduction strength to body weight (BW) ratios on RTS testing post-ACLR | 528 participants 292 males, 236 females Mean age (SD) = 24.75 (11.74) Graft type: NR | Isokinetic knee extension and flexion strength, IKDC, ACL-RSI, flexion and extension ROM deficit, SL balance deficit, SHD, THD, CHD, 6MTH | NR | Isometric hip abduction strength | - 68.9% had a low strength:BW ratio<br>- More females and ↑ BMIs were seen in the <33% group (*p*<.05)<br>- At RTS, the <33% group had ↓ IKDC (*p*<.01), ACL-RSI (*p*<.01), and isokinetic hamstring peak torque (*p*=.04)<br>- At 2 years, the <33% group reported ↓ SANE scores (*p*=.05), with no significant differences in re-injuries |
| **Tallard, Hedt (92)** Cross-sectional study | To assess the effect of fatigue on performance of various hop tests used in clinical rehabilitation settings | 21 participants 15 male, 6 female Mean age (SD) = 24.6 (9.3) Graft type: HT autograft, PT autograft, allograft (n=NR) | Isometric knee extension and flexion strength, SHD, THD, CHD, 6MTH, MRH, LRH, VJ | I | RTS test in fatigued state (FS) | - Differences between limbs were seen in all hop tests in NFS, with the ACLR limb showing reduced performance (↓5.4-9.1%, p<0.05)<br>- In FS, significant differences remained for the CHD (↓4.9%), MRH (↓7.1%), LRH (↓5.5%), and VJ (↓10.0%) (*p*<0.05)<br>- Comparing NFS to FS, only the control limb showed decreased performance in |

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| | | | | | | the THD (↓7.4%), CHD (↓8.7%), and LRH (↓5.2%) ($p$<0.05) |
| **King, Richter (93)** Prospective cohort study | To assess differences in strength, jump, CoD performance, and 3D biomechanics between athletes who reinjured their ACL (RI) and those without reinjury (NRI) after 2 years, and to evaluate if these differences predict reinjury | 88 male athletes<br>Age = 18-35<br>Graft type: HT autograft (68), PT autograft (20) | isokinetic knee extension and flexion strength, SLCMJ, SHD, DLDJ, planned CoD, unplanned CoD, IKDC, Marx activity scale, ACL-RSI | I | Number of athletes who reinjured (RI) | - No differences were found in strength or performance on the ACLR side or in symmetry<br>- Biomechanical differences in the RI group were noted in the sagittal plane during the double-leg drop jump (ES=0.59-0.64) and in frontal plane asymmetry during unplanned CoD (ES=0.61-0.69)<br>- Multivariate regression showed limited ability to predict ACL reinjury (AUC 0.67-0.75). |
| **Losciale, Ithurburn (94)** Prospective cohort study | To evaluate the sagittal plane knee joint loading patterns during a DL landing task in | 205 participants (57 control)<br>64 male, 141 female | Isometric knee extension strength, SHD, THD, CHD, 6MTH, IKDC, | I | vGRF, KFA, KEM | - 26.4% passed all RTS tests<br>- 73.6% failed at least one<br>- LSI cut off was not met by 41.9% on quadriceps strength, 24.3% on the SHD, 17.6% on the THD LSI, 23% on the CHD, |

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| | young athletes who passed or failed RTS tests post-ACLR and in uninjured athletes | Mean age (SD) = 16.7 (2.77)<br>Graft type: HT autograft (82), PT autograft (55), allograft (11) | | | | 18.9% on the 6MTH, and 47.3% scored <90 on the IKDC<br>- The involved limb showed greater KFA at landing (*p*<.001), while the RTS-FAIL group had lower peak knee flexion during weight acceptance than control (*p*<.001)<br>- RTS-FAIL group had lower peak vGRF and internal KEM compared to RTS-PASS and CTRL (*p*<.05), with significant interactions for both measures (*p*<.001) |
| **Hadley, Rao (28)**<br>Prospective cohort study | To assess how a 'Safer Return to Play Checklist' combining subjective and objective functional tests affects injury rates post-ACLR | 184 patients analysed<br>88 male patients, 96 female<br>Mean age (SD); 19.2 (2.1)<br>Graft typr: HT autograft (67), PT autograft (99), PT | Effusion, ROM, laxity, thigh circumference, IKDC, FMS, SHD, THD, CHD, 6MTH, pro agility, movement assessment | NR | Number of pt who RTS, reinjury rate | - 146 patients passed the checklist, and 38 did not<br>- Among those who passed, 16.4% sustained an injury to either knee, compared to 26.3% from the group that did not pass (*p*=.162)<br>- In the group that passed, 5.5% had an ipsilateral knee injury, compared to 18.4% in the group that did not pass (*p*=.017) |

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| | | allograft (5), HT allograft (3), tibialis anterior allograft (1), HT autograft with allograft augmentation (9) | | | | |
| **Paterno, Thomas (95)** Prospective, longitudinal, observational cohort study | To identify associations between knee-related confidence, meeting RTS criteria, and future second ACL injury risk | 159 participants 47 male, 112 female Mean age (SD); 17.2 (2.6) Graft type: NR | Isometric knee extension strength, SHD, THD, CHD, 6MTH, KOS-QOL, IKDC | I, II | Reinjury rate | - High knee-related confidence at RTS: 37.7%<br>- 26.4% met RTS criteria<br>- 22% sustained second ACL injury post-RTS<br>- Higher proportion of confident participants met RTS criteria (*p*=0.001)<br>- Confident participants meeting all RTS criteria had a 10x higher risk of second ACL injury (*p*=0.02) |
| **Ronden, Koc (96)** Prospective cohort study | To determine the percentage of patients passing the BIA RTS test | 103 patients 78 male, 25 female | DL and SL stability test, SL CMJ, CMJ, TL-PJ, OL-SY, TL-QF | I, II, “other” | | - 17.5% passed RTS at 9 months after ACLR reconstruction |

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| | post-ACLR, and evaluate the association between passing the RTS test and PROMS | Mean age (SD); 19.75 (11)<br>Graft type: PT autograft | | | | - PROMs were not statistically significant different between the pass and fail groups |
| **Ueda, Matsushita (97)**<br>Cross-sectional study | To examine whether patients who met 1 RTS criterion had higher psychological readiness than those who did not meet any of the criteria and if those who met more had higher psychological readiness | 144 patients<br>82 males, 62 females<br>Mean age (SD); 25.9 (8.1)<br>Graft type: HT autograft, PT autograft (n=NR) | Isokinetic knee extension and flexion strength, SHD, IKDC, ACL-RSI | NR | Knee laxity, heel-height difference | - 16.0% met none, 18.7% met 1, 23.6% met 2, 24.3% met 3, and 17.4% met all 4 criteria<br>- Higher ACL-RSI scores associated with meeting hamstring strength LSI ($p$=.002), single-leg hop LSI ($p$=.004), and IKDC score ($p$<.001)<br>- Significant ACL-RSI score differences in none vs. 2, 3, or 4 criteria, and 1 vs 4 criteria ($p$<.001) |

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| **van Melick, Pronk (98)** Prospective cohort study | To assess if second ACL injury rate 2 years after ACLR in those who RTS was associated with meeting RTS criteria, and to determine why athletes do not return to their preinjury level of sport | 175 athletes<br>123 male, 52 female<br>Mean age (SD); 24 (6)<br>Graft type: HT autograft | Isometric knee extension, flexion and hip abduction strength, eccentric hamstring strength, SLVJ, SHD, SH, SLHAH, CMJ (assessed with LESS), KOOS, K-SES | I | Level of sport resumed, reason for not resuming the same level of sport, reinjury rate | - 82% completed the questionnaire, 97 athletes returned to pivoting sports, and 7 sustained a second ACL injury<br>- Meeting the hop test battery RTS criterion (*p*=.047) and SLHAH test (*p*=.031) significantly reduced the second ACL injury rate<br>- Combined RTS criteria did not show a significant association with the injury rate |
| **Broman, Piussi (99)** Cross-sectional study | To determine pass rates for clinician friendly RTS test batteries (CF) and the relationship between passing CF test batteries and passing gold standard RTS test | 588 patients<br>285 male, 303 female<br>Mean age (SD); 29.3 (9.8)<br>Graft type: HT autograft (479), PT autograft (98) | Isokinetic knee extension and flexion strength, SLVJ, SHD, SH, K-SES, ACL-RSI | I, II | Tegner score | - The pass rate for the GS test battery was 28%, and the CF test battery was 27%<br>- Among the CF test batteries most closely related to the GS test, 49% to 51% of patients who passed each CF test battery also passed the GS test battery |

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| | batteries (GS) post-ACLR | | | | | |
| **Correa, Verhagen (100)** Cross-sectional study | To compare the performance in RTS tests between athletes who were psychologically ready and not ready to return to unrestricted training or competitions post-ACLR | 35 male footballers Mean age (SD); 22 (7) Graft type: HT autograft | SL squat, CHD, MICODT, RAT, ACL-RSI | I | FPKPA, TSK-11, IKDC | - Those not ready to RTS had lower performance on the MICODT (*p*<0.001) and RAT (*p*=0.004) tests and higher FPKPA (*p*<0.001)<br>- The not ready to RTS group had lower IKDC (*p*<0.001) and higher TSK- 11 (*p*<0.001) scores |
| **Kiani Haft Lang, Mofateh (52)** Cross-sectional study | To compare the neurocognitive functions between healthy controls and ACLR athletes who passed or failed RTS tests | 45 male footballers Mean age (SD); 23.6 (2.73) Graft type: NR | Isometric knee extension strength, SHD, THD, CHD, 6MTH, KOS-ADLS, GRS | I | CANTAB | - Neurocognitive deficits were seen in both groups when comparing CANTAB scores<br>- The RTS fail group had higher 5-choice movement time than both the RTS pass (*p*=.02) and healthy groups (*p*=.01) but had lower stop signal reaction time (*p*=.03 vs. healthy; *p*=.001 vs. pass) and successful stops (*p*=.02) |

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| | | | | | | - Both ACLR groups showed greater between errors (*p*<.001, *p*=.008) and reaction latency (*p*=.002, *p*=.01) than the healthy group |
| **Maestroni, Turner (101)** Cross-sectional study | To examine the utility of the TSA in aiding RTS decision-making post-ACLR | 95 male footballers Mean age (SD); 24.45 (7.7) Graft type: HT autograft (19), PT autograft (76) | Isokinetic knee extension and flexion strength, DL CMJ, SL CMJ | I | TSA | - large difference in TSA score between the ACLR and uninjured groups (*d*=0.84; *p*<.0001)<br>- For each increase of 1 unit in the TSA, the odds of belonging to the ACLR group decreased by 74% (95% CI, 0.19-0.56)<br>- The frequency of reinjured players was higher in the low (4/7) TSA tertile compared with the medium (2/7) and high (1/7) |
| **Weber, Müller (102)** Cross-sectional study | To investigate the relationship between LSI of hop tests as an indication of performance and the total score of a movement | 34 participants 18 males, 16 females Mean age (SD); 24.2 (8.2) Graft type: HT autograft (29), QT autograft (5) | VJ, SHD, SH | NR | "Quality First" score | - The correlation test between the LSI and the "Quality First" score showed no correlation for all three jumps (*r*=−0.1–0.02, *p*=0.65–0.93) |

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|---|---|
| | quality<br>assessment |

*Note: ACL-RSI = Anterior Cruciate Ligament Return to Sport after Injury Scale, AUC = Area Under the Curve, BW = Body Weight, CHD = Cross-Over Hop for Distance, CoD = Change of Direction, CMJ = Countermovement Jump, DL = Double Leg, DJ = Drop Jump, EPIC = Estimated Pre-Injury Capacity, FMS = Functional Movement Screen, GRS = Global Rating of Symptoms, H:Q ratio = Hamstring-to-Quadriceps Ratio, IKDC = International Knee Documentation Committee, LSI = Limb Symmetry Index, MVIC = Maximum Isometric Volitional Contraction, MRH = Medial Rotation Hop, NR = Not Reported, RFD = Rate of Force Development, RSR = Reactive Strength Ratio, SL = Single Leg, THD = Triple Hop for Distance, TCpk = Total Concentric Peak, vGRF = Vertical Ground Reaction Force, YBT = Y-Balance Test, KOS-ADLS = Knee Outcome Survey-Activities of Daily Living Scale, 6MTH = 6-Month Follow-up, MICODT = Modified Illinois Change of Direction Test, RAT = Return to Activity Test, K-SES = Knee-Specific Evaluation Scale, LESS = Landing Error Scoring System, SLHAH = Single Leg Hop and Hold, OL-SY = One Leg Speedy Jump, TL-QF = Two Leg Quick Feet, TL-PJ = Two Leg Plyometric Jump, PROMS = Patient-Reported Outcome Measures, PT = Patella tendon, QT = Quadriceps tendon, HT = Hamstring tendon, SHD = Single Hop Distance, ROM = Range of Motion, KFA = Knee Flexion Angle, VJ = Vertical Jump, LRH = Lateral Rotation Hop, QASLS = Qualitative Assessment of Single-Leg Landing, pedi-IKDC = Pediatric-IKDC, TSK-11 = Tampa Scale of Kinesiophobia (11-item version)*

## 2.5 Results

The initial search identified 1,703 studies, of which 33 met the inclusion criteria. Of these, 11 were cross-sectional studies, 14 were prospective cohort studies, four were observational cohort studies, one was a retrospective cohort study, two were controlled laboratory studies, and one was a case-control study. The studies provided broad geographical representation, including North and South America, Europe, Asia, and Oceania.

A total of 6,010 participants were included across the studies, with 64% being male (n = 3,871) and 36% female (n = 2,139). The mean age (SD) of participants was 24.8 (3.7) years. Among the studies, 16 focused on athletes from level I sports (4, 46, 47, 52, 77, 78, 84, 85, 88, 89, 92, 93, 94, 98, 100, 101), seven focused on level I and II sports (79, 81, 83, 86, 92, 95, 96), and two on level I, II, and III sports (68, 80). Eight studies did not specify the type of sport participation but met the inclusion criteria and were included in the review (14, 28, 82, 87, 90, 91, 97, 102).

The most frequently used graft type in this review is the hamstring tendon autograft, representing approximately 70% of participants from studies reporting graft type. Patellar tendon autografts are the second most used, accounting for approximately 8% of participants. Iliotibial band (ITB) and quadriceps tendon autografts each make up 1% of participants. Five studies did not report the graft type (47, 52, 81, 91, 95), accounting for approximately 20% of participants.

Four studies involved professional athletes (46, 77, 88, 101), one study included both professional and amateur athletes (90), while the remaining studies involved amateur and recreational athletes, or did not report the level of sport participation (4, 14, 28, 47, 52, 68, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 89, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 102).

*Table 5: RTS Criteria Themes*

| Criteria | Detail | | References |
|---|---|---|---|
| **Time** | ≥4 months | | |
| | | Level III | (90) |
| | ≥6 months | | (77, 78) |
| | | Level II | (90) |
| | ≥9 months | | |
| | | Level I | (90) |
| **Strength** | **Knee extension MVIC** | | |
| | 90° flexion | | |
| | | Pre-injury level | (77) |
| | | ≥80% LSI | (82) |
| | | ≥85% LSI | (80) |
| | | ≥90% LSI | (47, 52, 79, 94) |
| | 60° flexion | | |
| | | ≥90% LSI | (95, 98) |
| | **Knee extension IKD** | | |
| | 60°/s | | |
| | | ≥85% LSI | (87, 91) |
| | | ≥90% LSI | (4, 46, 68, 81, 84, 86, 89, 93, 97) |
| | | 260% (+/-40%) BM | (84) |
| | | >3.0 Nm/kg | (86, 89) |
| | | Composite score (TSA) | (101) |
| | 90°/s | | |
| | | ≥90% LSI | (81, 99) |
| | | >3.0 Nm/kg | (81) |
| | 180°/s | | |
| | | ≥80% LSI | (82) |
| | | ≥85% LSI | (91) |
| | | ≥90% LSI | (81, 86, 89) |
| | 300°/s | | |

| | | |
|---|---|---|
| | ≥85% LSI | (91) |
| | ≥90% LSI | (86, 89) |
| | Pre-injury level | (77) |
| | Not reported | (92) |
| | **Knee flexion MVIC** | |
| | ≥85% LSI | (80) |
| | ≥90% LSI | (14, 98) |
| | **Knee flexion eccentric** | |
| | ≥90% LSI (HHD) | (98) |
| | **Knee flexion IKD** | |
| | 60°/second | |
| | ≥90% LSI | (81, 84, 86, 89, 97) |
| | Composite score (TSA) | (101) |
| | 90°/second | |
| | ≥90% LSI | (81, 83, 99) |
| | 180°/second | |
| | ≥90% LSI | (81, 86, 89, 91) |
| | 300°/second | |
| | ≥90% LSI | (86, 89, 91) |
| | **H:Q ratio (%)** | |
| | IKD 300°/s | |
| | >55 for females, >62.5% for males | (81, 86, 89) |
| | MVIC | |
| | ≥85% LSI | (80) |
| | **Hip abduction MVIC** | |
| | >33% BW | (91) |
| | ≥90% LSI | (14, 98) |
| | **Hip adduction MVIC** | |
| | ≥90% LSI | (14) |

| | | | |
|---|---|---|---|
| **Jump and hop performance** | **Distance hop tests (≥1 of SHD, THD, CHD, 6MTHT); non-fatigued state** | | |
| | | ≥100% LSI | (92) |
| | | ≥90% LSI | (4, 14, 28, 46, 47, 52, 68, 78, 79, 81, 83, 85, 86, 88, 89, 90, 91, 93, 94, 97, 98, 99, 100) |
| | | ≥90% EPIC | (47) |
| | | ≥85% LSI | (80, 87, 90) |
| | | ≥80% LSI | (90) |
| | | "Satisfactory" | (82) |
| | **THD** | | |
| | | CT, FT, RSR ≥90% LSI | (88) |
| | **Distance hop tests (≥1 of SHD, THD, CHD, 6MTHT); fatigued state** | | |
| | | ≥100% LSI | (92) |
| | **Side hop test** | | |
| | | ≥90% LSI | (86, 89, 98, 99) |
| | **DLCMJ** | | |
| | | ≥80% LSI (non-dominant leg), ≥90% LSI (dominant leg) | (96) |
| | | Composite score (TSA) | (101) |
| | **SLCMJ/SLVJ/SLJ** | | |
| | | ≥80% LSI (non-dominant leg), ≥90% LSI (dominant leg) | (96) |
| | | ≥90% LSI | (83, 84, 93, 98) |

| | | |
|---|---|---|
| | >17cm (+/-4cm) | (84) |
| | Cut-off not reported | (99) |
| | Composite score (TSA) | (101) |
| | **SLDJ** | |
| | ≥90% LSI | (93) |
| | **SLHAH** | |
| | ≥90% of SLHD test | (98) |
| | **LESS** | |
| | <5 | (81, 86, 89) |
| | <6 | (98) |
| **Biomechanical assessment** | **Running/gait/CoD kinematics** | |
| | 3D motion capture | (78, 93) |
| | **Jump/landing** | |
| | 3D motion capture | (93) |
| | Qualitative score | (90, 102) |
| | ≥80% LSI | (28) |
| | **Balance/stability** | |
| | DLST, SLST | |
| | ≥80% LSI (non-dominant leg), ≥90% LSI (dominant leg) | (83, 96) |
| | YBT(-LQ) | |
| | ≥90% LSI | (14) |
| | Cut-off not reported | (91) |
| | **FMS** | |
| | >14 | (28) |
| **CoD and Agility** | **CoD** | |
| | MICODT | (90, 100) |

| | | |
|---|---|---|
| | Pro-agility | (28) |
| | 90° planned and unplanned | (93) |
| | Running t-test | |
| | ≥90% LSI | (46) |
| | **Agility** | |
| | TL-QF (s) | |
| | ≥80% LSI (non-dominant leg), ≥90% LSI (dominant leg) | (83, 96) |
| | OL-PJ (s) | |
| | ≥80% LSI (non-dominant leg), ≥90% LSI (dominant leg) | (83, 96) |
| | OL-SY (s) | |
| | ≥80% LSI (non-dominant leg), ≥90% LSI (dominant leg) | (83, 96) |
| | RAT | (100) |
| **Patient reported measures** | **ACL RSI** | |
| | >55 | (81, 90, 96) |
| | >56 | (86, 89) |
| | >60 | (100) |
| | >65 | (68, 90) |
| | >75 | (90, 99) |
| | Cut-off not reported | (80, 93) |
| | **IKDC** | |
| | ≥85 | (68, 96) |
| | ≥90 | (94, 95, 97) |
| | ≥95 | (85) |

| | | |
|---|---|---|
| | within 15% of healthy, gender- and age-matched controls | (86, 89) |
| | Cut off not reported | (28, 52, 80, 81, 83, 91, 93, 100) |
| | **TSK(-11)** | |
| | >7.5 | (99) |
| | Cut-off not reported | (80) |
| | **KOS-ADLS** | |
| | >90% | (47) |
| | Cut-off not reported | (4, 78, 79) |
| | **KOS-QOL** | |
| | | |
| | **GRS** | (4, 78, 79) |
| | >90% | (47) |
| | Cut-off not reported | (95) |
| | **GKRS** | |
| | Cut-off not reported | (52) |
| | **Marx Activity Scale** | |
| | Cut-off not reported | (93) |

*Note: ACL RSI = Anterior Cruciate Ligament Return to Sport Index, BW = Body Weight, CHD = Crossover Hop for Distance, CoD = Change of Direction, CT = Contact Time, DLCMJ = Double-Leg Countermovement Jump, DLST = Double-Leg Stance Test, EPIC = Estimated Pre-injury Capacity, FMS = Functional Movement Screen, FT = Flight Time, GKRS = Global Knee Rating Scale, GRS = Global Rating Scale, H:Q = Hamstring to Quadriceps ratio, HHD = Hand-Held Dynamometer, IKDC = International Knee Documentation Committee, IKD = Isokinetic Dynamometer, KOS-ADLS = Knee Outcome Survey-Activities of Daily Living Scale, KOS-QOL = Knee Outcome Survey-Quality of Life, LESS = Landing Error Scoring System, LSI = Limb Symmetry Index, MICODT = Modified Illinois Change of Direction Test, MVIC = Maximal Isometric Voluntary Contraction, MVIC = Maximal Voluntary Isometric Contraction, OL-PJ = One-Legged Plyometric Jump Test, OL-SY = One-Legged Speedy Jump Test, RAT = Reactive Agility Test, RSR = Reactive Strength Ratio, SHD = Single Hop for Distance, SLCMJ = Single-Leg Countermovement Jump, SLDJ = Single-Leg Drop Jump, SLHAH = Single-Leg Hop and Hold, SLHD = Single-Leg Hop for Distance, TL-PJ = Two Leg Plyometric Jump, SLST = Single-Leg Stability Test,* *SLCMJ = Single-Leg Countermovement Jump, TSK = Tampa Scale for Kinesiophobia, TSA = Total Score of Athleticism, 6MTHT = Six-Meter Timed Hop Test, THD = Triple Hop for Distance, TL-QF = Two Leg-Quick Feet, YBT(-LQ) = Y-Balance Test (Lower Extremity)*

**2.6 Return to Sport Criteria**

2.6.1 Time

Time is a key factor for RTS decision-making, however only three studies explicitly report using time as an RTS criterion (77, 78, 90). Two of these studies describe an accelerated rehabilitation programme aimed at RTS within six months (77, 78). The third study sets specific timeframes for RTS based on the level of sport: level III at a minimum of four months, level II at six months, and level I at nine months (90).

2.6.2 Strength

Strength assessments were reported in nearly 80% of the studies in this review (4, 14, 47, 52, 68, 77, 78, 79, 80, 81, 82, 83, 84, 86, 87, 89, 91, 92, 93, 94, 95, 96, 97, 98, 99, 101). Most studies included knee extension strength: 35% assessed a maximal voluntary isometric contraction (MVIC) (47, 52, 77, 79, 80, 82, 94, 95, 98), while 65% assessed torque using isokinetic dynamometry (IKD) (4, 46, 68, 77, 81, 82, 83, 84, 87, 89, 91, 92, 93, 97, 99, 101, 103). Over half of these studies also measure knee flexion strength (61%): three used MVIC (14, 80, 98), one assessed eccentric strength (98), and nine used IKD (81, 83, 84, 89, 91, 97, 99, 101, 103). There is some variation in MVIC and in IKD testing protocols (90- or 60-degrees flexion angles, and 60, 90, 180, or 300 degrees per second speeds, respectively).

Among studies assessing strength, 70% used an LSI of ≥90% as the RTS cut-off (4, 14, 46, 47, 52, 68, 79, 81, 83, 84, 89, 93, 94, 97, 98, 99, 103), while 12% used an LSI of ≥85% (80, 87, 91), and one study applied an LSI of ≥80% (82). Six studies utilised alternatives to LSI: one used pre-injury strength levels as a threshold (77), another used body weight percentages (260 ± 40%) (104), and the remaining three used force per kilogram of body mass (e.g., >3.0 Nm/kg for knee extension) (81, 89, 103). The final study used knee flexor and extensor strength to form part of a composite score of strength, power, and reactive strength (Total Score of Athleticism, TSA) (101).

Four studies incorporated the hamstring-to-quadriceps (H:Q) ratio for RTS decision-making (80, 81, 89, 103). Three of these studies assessed the H:Q ratio at 300 degrees per second, recommending thresholds of >62.5% for males and >55% for females (81, 89, 103), while the other study used an MVIC pass threshold of ≥85% LSI (80).

Finally, three studies assessed hip strength (14, 91, 98). Two studies measured hip abduction MVIC with an LSI of ≥90% as the RTS cut-off (14, 98), while one study used a percentage of body weight (33%) (91). One study also used hip adduction MVIC, setting an LSI cut-off of ≥90% (14).

### 2.6.3 Jump and hop performance

Over three quarters of the studies (79%) used a hop test battery with one or more horizontal hop tests, including 6 meter timed, single, triple, and triple crossover hops (4, 14, 28, 46, 47, 52, 68, 78, 79, 81, 82, 83, 85, 87, 88, 89, 90, 91, 92, 93, 94, 97, 98, 99, 100, 103). One study also assessed horizontal hop performance under fatigued conditions (92). Nearly all the studies assessing horizontal hop tests set a pass threshold of ≥90% LSI (96%) (4, 14, 28, 46, 47, 52, 68, 78, 79, 81, 83, 85, 88, 89, 90, 91, 93, 94, 97, 98, 99, 100, 103). In addition to hop-for-distance tests, four studies included the side-hop test with a ≥90% LSI cut-off (86, 89, 98, 99).

Several studies also included vertical jump tests. Seven studies described using either a double leg countermovement jump (CMJ) or a single-leg vertical jump (VJ) in RTS decision-making (83, 84, 93, 96, 98, 99, 101). There is variability in pass criteria, with cut-off thresholds ranging from 80% to 90% for jump height or LSI. One study used a double and single leg CMJ as part of a composite score (TSA), as previously described (101). Additionally, one study used a single leg drop jump (DJ) to assess reactive strength indexes (RSI), using ≥90% LSI as an RTS cut-off (93). RSI is a measure of an individual's reactive strength capabilities derived from ground reaction time and flight time (105).

Finally, four studies assessed a jump and landing task using the qualitative Landing Error Scoring System (LESS) (81, 89, 98, 103). Three of these studies had an RTS cut-off score of less than five (81, 89, 98, 103), and the remaining study used a score of less than six (98).

2.6.4 Biomechanical assessment

Two studies assessed gait using three-dimensional (3D) motion capture technology (78, 93). Jump and landing kinematics were examined in three studies, with one utilising 3D motion capture (93), and two employing the LESS (28, 90, 102).

Four studies assessed balance and stability (83, 96), with two using double and single leg stability tests, setting different LSI thresholds for the non-dominant (≥80%) and dominant legs (≥90%) (83, 96). The other two studies utilised the Y-Balance Test (YBT) (14, 91). A final study used the Functional Movement Screen (FMS), a standardised screening tool designed to assess movement patterns and identify potential weaknesses, imbalances, or mobility issues (28).

2.6.5 Change of direction and agility

Four studies evaluated CoD in the context of RTS (28, 90, 93, 100). Two studies used the Modified Illinois Change of Direction Test (MICODT) (90, 100), one employed the Pro-Agility Test (28), one incorporated a 90 degree planned and unplanned direction change test (93), and one used a running T-Test (46). A cut-off criterion for RTS was described in the study using the T-Test, which reported a threshold of ≥90% LSI for time completion.

Agility was assessed in three studies (83, 96, 100). Two studies employed the Two-Leg Quick Feet Test (TL-QF), the One- and Two-Leg Plyometric Jump Test (O(T)L-PJ), and the One-Leg Speedy Test (OL-SY), using LSI thresholds of ≥80% for the non-dominant leg and ≥90% for the dominant leg (83, 96). The third study utilised the Reactive Agility Test (RAT) (100).

2.6.6 Patient-reported measures

Patient-reported outcome measures (PROMs) were described in 62% of the included studies (28, 52, 80, 81, 83, 85, 86, 89, 91, 93, 94, 95, 96, 97, 100, 106). The International Knee Documentation Committee (IKDC) questionnaire was the most frequently used PROM, featuring in 15 studies (28, 52, 80, 81, 83, 85, 86, 89, 91, 93, 94, 95, 96, 97, 100), followed by the Anterior Cruciate Ligament-Return to Sport after Injury (ACL-RSI) scale, which was reported in 10 studies (80, 81, 85, 86, 89, 90, 93, 96, 99, 100). RTS cut-off thresholds ranged from ≥85 to ≥95 for the IKDC, and >55 to >75 for the ACL-RSI.

Other PROMs used in the studies included in this review are the Tampa Scale of Kinesiophobia (TSK) (80, 99), the Knee Outcome Survey-Activities of Daily Living Scale (KOS-ADLS) (4, 47, 78, 79), the Global Rating Scale (GRS) (4, 47, 78, 79, 107), the Global Knee Rating Scale (GKRS) (52), and the Marx Activity Scale (93). Only two studies described specific cut-off values for RTS: a TSK (-11) score of <7.5 (99) and GRS or KOS-ADLS scores of >90% (47).

## 2.7 Discussion

### 2.7.1 Time

The remodelling of the ACL graft may take from six to 36 months (21), though exact timelines are debated (20). This may explain why few studies incorporate time as an RTS criterion. Although earlier studies used accelerated rehabilitation approaches to target RTS at six months (77, 78), more recent evidence has reshaped practices, establishing nine months as the recommended minimum RTS timeframe (20, 45, 93).

Substantial evidence emphasises the importance of delaying RTS to reduce reinjury risk. Beischer, Gustavsson (12) found that young athletes who RTS before nine months face a sevenfold higher risk of a second injury, even after achieving 90% knee strength LSI. Grindem, Snyder-Mackler (4) reinforce this, demonstrating that each additional month of RTS delay between six and nine months decreases reinjury risk by 51%.

Nevertheless, some experts advocate for more conservative timelines for high-risk populations. Nagelli and Hewett (65) recommend delaying RTS for up to two years in certain groups, such as females, highlighting the importance of tailoring RTS protocols to individual risk profiles.

### 2.7.2 Strength

Strength measurement is commonly used for RTS decision-making. IKD is considered the gold standard for strength assessment and is the most frequently used method in this review (37). However, handheld dynamometry (HHD) and portable fixed dynamometry (PFD) are more commonly used in clinical practice to assess MVIC due to their affordability and convenience (35, 36). PFD has demonstrated high test-retest reliability, however HHD is considered poor in this respect (39). However, both methods are specific to the joint angle tested, therefore the results should be interpreted with caution.

The most common strength cut-off for RTS found in this review (≥90% LSI at 60 degrees per second) is supported by the wider literature (4, 46, 108). However, several researchers recommend higher LSI cut-offs for athletes returning to level I sports (109, 110), a stance supported by recent clinical guidelines suggesting 100% symmetry for elite athletes returning to pivoting sports (20). As uninjured athletes demonstrate an LSI of 96% (109), the widely adopted ≥90% LSI cut-off may prove insufficient for informing RTS decisions.

Moreover, there is growing criticism of LSI in RTS decision-making due to reduced contralateral limb strength following ACLR surgery, limb dominance, and pre-existing interlimb asymmetries affecting its accuracy as an RTS measure (111, 112, 113). Wellsandt, Failla (47) found that only 28.6% of athletes who achieved ≥90% strength LSI post-ACLR reached their estimated pre-injury capacity (EPIC). To improve the validity of LSI, baseline measurements pre-surgery, and setting EPIC-based thresholds are recommended. Alternatively, Buckthorpe, Tamisari (114) support using body weight percentages, suggesting that those returning to pivoting sports require ≥90% LSI and a one-repetition maximum (1RM) of at least twice body weight on a unilateral leg press.

A further limitation of strength testing relates to AMI, a reflexive neuromuscular inhibition arising from altered sensory input following knee injury (48). AMI can reduce voluntary quadriceps activation despite adequate muscle mass, meaning that observed strength deficits may reflect impaired neural drive rather than true force-generation capacity. This may partially explain why many athletes struggle to restore quadriceps function despite comprehensive rehabilitation (48). Incorporating assessment of voluntary activation and neuromuscular function may therefore enhance the interpretability of strength measures used in RTS testing.

Finally, H:Q ratio is rarely used to inform RTS decision-making, likely due to conflicting evidence for its utility. Although research suggests that H:Q ratio is not an independent risk factor for primary ACL injuries (115), it is associated with an increased risk of graft rupture (46). As the hamstring counteracts anterior tibial translation caused by quadriceps contraction, a lower H:Q ratio could indicate a higher risk of re-injury (116).

Supporting this, Kyritsis, Bahr (46) found a 10.6-fold increase in graft rupture risk for every 10% decrease in H:Q ratio among male athletes, suggesting it is an important assessment measure during RTS testing.

2.7.3 Jump and hop performance

The literature links hop test batteries to a reduced risk of graft or contralateral ACL rupture (4, 6, 43). Whilst there is agreement across these studies for the inclusion of a horizontal hop test battery, inconsistencies exist in how these tests are used to assess knee function, identify injury risk, and predict rehabilitation outcomes or performance. Various factors contribute to these inconsistencies, including testing errors which impact reliability (113), and as they primarily reflect hip and ankle function (117, 118).

Although the ≥90% LSI threshold for horizontal hop tests is widely accepted for RTS clearance, some researchers suggest this is insufficient given the decline in contralateral limb performance post-ACLR (47). Davies, Myer (113) argue four horizontal hop tests may not be more effective at detecting abnormalities than two and recommend focusing on single and triple hop tests. Kotsifaki, Van Rossom (119) demonstrate that the landing phase of these tests are sensitive for evaluating knee energy absorption efficiency.

However, traditional hop and jump tests overlook the skill-acquisition and perceptual-cognitive elements underpinning non-contact ACL injury mechanisms. Most ACL injuries occur when athletes fail to interpret environmental cues, anticipate movement patterns, or adapt to unplanned stimuli, leading to high-risk biomechanics under time pressure (49, 51, 120). Incorporating dual-task and reactive-stimulus paradigms into jump testing may enhance the ecological validity and align more closely with the perceptual-motor demands that contribute to non-contact ACL injury.

Correspondingly, Simon, Millikan (56) augmented these hop tests with visually mediated response time using a light-timing system to introduce neurocognitive, reactive, and anticipatory components under dual-task conditions. By performing hops under both standard and neurocognitive conditions, a dual-task cost can be calculated, quantifying the degree of neurocognitive reliance. Grooms, Chaput (55) propose that a dual-task cost exceeding 10% may indicate heightened neurocognitive reliance, and therefore an increased risk of re-injury. This enhances the ecological validity of hop testing by simulating sport-specific scenarios, targeting cross-modal neural processing, and supporting more informed RTS decisions.

Finally, advanced technology such as force platforms, wireless sensors, and 3D motion capture has facilitated the use of tests such as the CMJ and single-leg VJ. These are more sensitive to detecting asymmetries compared to horizontal hop tests, partly due to the higher knee forces generated (119, 121). They are becoming the gold standard for identifying kinematic and kinetic deviations (122, 123). A recent study by Pontillo, Hines (123) found that individuals post-ACLR showed significant deficits in the explode and drive phases of the force-time curve during vertical jump tests, as well as load-to-explode ratios. This highlights a reduced ability to generate, sustain, and transfer force efficiently during explosive movements. Importantly, these deficits were predictive of injury in this study. Nevertheless, their limited adoption in this review may reflect the expense and training required for the use of specialised equipment.

### 2.7.4 Biomechanical assessment

Reliance on high-tech tools is similarly evident in studies assessing biomechanics using 3D motion capture. King, Richter (93) found interlimb differences in sagittal plane mechanics during drop jump tests, even in athletes who passed traditional RTS assessments. By contrast, Di Stasi, Logerstedt (78) found only athletes who failed a similar RTS assessment at six months post-ACLR demonstrated significant asymmetries in sagittal plane kinematic and kinetic variables at the knee.

While biomechanical assessments provide valuable insights for RTS decision-making, the practical limitations of the technology required make them less feasible for widespread application. Consequently, researchers have explored alternatives to bridge this gap. Franck, Saithna (90) introduced the Qualitative Assessment of Single-Leg Landing (QASLS), which evaluates movement strategies during SL jump and landing tasks as part of a composite score. Hadley, Rao (28) proposed an assessment focusing on hip stability, shock absorption, and pelvic and trunk control. Weber, Müller (102) developed a qualitative tool to assess kinematics during three single leg hop and jump tasks. While these tools demonstrated reliability, the inherent subjectivity of qualitative measures presents accuracy concerns (124).

Balance assessments are suggested to help RTS decision-making due to evidence that athletes post-ACLR exhibit reduced postural stability in SL stance compared to uninjured controls, even when meeting other RTS criteria (125). However, this evidence derives from assessments using devices that objectively measure postural control under dynamic stress. Reliance on such equipment to assess balance may explain the infrequent inclusion of these assessments in this review.

Other examples of balance assessment that require minimal equipment include one- and two-leg balance tests and the YBT. These tests may reveal neuromuscular deficits not always detectable through strength or hop tests. Oleksy, Mika (126) demonstrated that footballers post-ACLR scored significantly lower on the YBT compared to uninjured players. However, others highlight that athletes often employ varied movement strategies during the YBT, limiting its ability to provide meaningful insights into joint kinematics or ACL reinjury risk (127). Moreover, balance tests fail to replicate the high-velocity, multidirectional demands of sports, reducing their specificity and applicability, therefore limiting their relevance to RTS decision-making.

#### 2.7.5 Change of direction and agility

Most ACL injuries occur during non-contact CoD movements (54, 120, 128), suggesting that RTS assessments may be inadequate if these movements are not addressed. Welling and Frik (129) emphasise the importance of RTS assessments that better reflect pivoting sports. They argue that without on-field assessments, clinicians have "incomplete information about a patient's physical capacity" (p. 6). This is supported by Kyritsis, Bahr (46), who included a timed running T-test in their RTS criteria, failure of which showed a fourfold increase in the risk of graft rupture. This test, together with the Pro-Agility and MICODT, are examples of planned CoD tests. While they clearly have merit, they may not capture the reactive and neurocognitive demands of sport, where athletes adapt their movements based on unpredictable situations (53). As mentioned, RTS carries environmental, cognitive and physical demands, which researchers suggest RTS criteria should better reflect (55).

Correspondingly, unplanned CoD movements have been shown to mimic knee mechanics associated with ACL injury risk (49). Knee loads during unplanned movements can be twice those of planned CoD movements (129). King, Richter (93) and Correa, Verhagen

(100) both include unplanned CoD tests in their studies; the unplanned 90-degree CoD test and the RAT. The former necessitates the athlete to react to a timing light, while the latter requires the athlete to respond to the assessor's cue during a sprint. Another example is demonstrated by Wilk, Thomas (130) in their theoretical model of reactive agility assessment, including variations of the running T-test and the L-test, where the direction of movement is instructed during a sprint. Incorporating on-field reactive tests in RTS assessments may better reflect the neurocognitive demands of sport, particularly for level I athletes, marking a more comprehensive approach, reflecting the specific demands of sport.

Nevertheless, reactive agility and CoD assessments have limitations, reflected in the low proportion of studies including these for RTS decision-making. These tests primarily evaluate performance based on interlimb timing, which may not detect underlying biomechanical asymmetries (46, 130).

As discussed, the widespread use of 3D motion capture is not feasible. Alternatives for CoD assessment are qualitative tools like the Cutting Movement Assessment Score (CMAS) (50), which has been validated for assessing knee abduction moments and whole-body kinetics. The CMAS requires video analysis of an agility test and has demonstrated excellent intra-rater reliability. Notwithstanding the issues associated with subjective measures, when used alongside interlimb timing assessments, tools like this could provide a more robust evaluation of reactive agility to help guide RTS.

#### 2.7.6 Patient-reported measures

PROMs are included in most of the studies, reflecting the recommendations of clinical guidance (20, 45). The ACL-RSI and IKDC are often used to assess subjective readiness to RTS (20, 131, 132), a trend seen in this review. Other PROMS, such as TSK and GRS, are occasionally used, however due to their low validity in patients with an ACL injury, ACL-RSI and IKDC are considered better measures of psychological readiness (133).

Webster and Feller (68) identified strong associations between self-reported measures of psychological readiness (IKDC and ACL-RSI) and RTS at 12 months post-ACLR, and individuals with higher scores demonstrate increased chances of returning to pre-injury performance (36). Furthermore, Müller, Krüger-Franke (80) found that athletes who did not RTS had significantly lower ACL-RSI scores at six and 12 months. This finding matches other studies, highlighting fear of injury as a common reason for unsuccessful RTS (132, 134, 135). Current research supports the continued use of these measures to identify low scores at critical milestones for clinicians to intervene and address concerns.

### 2.8 Recommendations

Drawing on the findings of this review, RTS following an ACLR should be based on a comprehensive, criteria-based approach that extends beyond arbitrary timelines. While a minimum delay of nine months is supported by robust evidence, this should be a consideration rather than a universal standard. High-risk groups, such as young or female athletes, may benefit from even more conservative timelines, potentially up to 18–24 months, particularly where psychological readiness or neuromuscular deficits persist.

Strength testing should remain a cornerstone of RTS decision-making. IKD provides ideal standardisation, but where unavailable, PFD is an acceptable alternative. However, ≥90% LSI alone is not sufficient. The author recommends including 1RM measures adjusted to body weight (e.g., ≥2x body weight unilateral leg press) and, where possible, referencing pre-injury baselines.

Functional testing should not rely solely on traditional horizontal hop tests. Incorporating vertical jump testing using force platforms, where available, adds sensitivity to detect asymmetries. If unavailable, single- and triple-hop tests remain useful, ideally performed under dual-task or reactive conditions to simulate sport-specific cognitive demands.

Agility and CoD assessments are essential, especially for athletes in level I sports. While planned CoD tests (e.g., T-test, MICODT) provide a performance baseline, incorporating reactive CoD tests such as the RAT or reactive 90-degree CoD test better replicate sport-specific demands. In the absence of advanced technology, clinicians can use dual task hop tests or reactive CoD drills to introduce neurocognitive load. Tools like the CMAS offer valuable insight into movement quality using only video footage, making them practical for wider clinical application.

Psychological readiness is critical. The ACL-RSI and IKDC should be included at six, nine, and 12 months post-op, with a low score triggering psychological intervention. Structured

RTS counselling or gradual exposure to sport-specific tasks can be implemented in those with low confidence or elevated fear of reinjury. A minimum ACL-RSI score of ≥65 to 70 may serve as a clinical threshold for RTS.

Finally, RTS protocols must be individualised and multidisciplinary, involving collaboration between the patient, surgeons, physiotherapists, sports physicians, and where appropriate, psychologists. Decisions should never be based on a single metric or time-based cutoff but rather a composite profile of physical, functional, biomechanical, and psychological readiness.

### 2.9 Strengths and Limitations

This scoping review has several limitations to consider when applying the findings in clinical or research settings. By design, scoping reviews do not require a formal assessment of bias or methodological quality, limiting the ability to critically evaluate the strength and reliability of the evidence. While the review offers an overview of published RTS research, it omits innovative or practice-based approaches.

Furthermore, limitations in the search strategy, including variations in RTS terminology and database coverage, could have resulted in missed studies. The exclusion of clinical commentaries and reviews, whilst intended to minimise interpretive and selection bias, may have inadvertently omitted valuable studies. Additionally, excluding non-English language publications likely overlooked relevant research. A further limitation is that screening and data extraction were completed by a single reviewer, which as previously mentioned increases the risk of selection bias or extraction errors.

Nonetheless, this scoping review offers a broad synthesis of evidence on RTS decision-making, providing valuable insights into current practices and highlighting key themes. It follows a rigorous methodology, ensuring consistency and reliability, and the identification of literature gaps provides clear direction for future research.

### 2.10 Conclusion

This scoping review underscores the multifaceted nature of RTS decision-making following ACLR surgery. Evidence supports delaying RTS to at least nine months to minimise reinjury risk, though recommendations vary for high-risk populations. Strength assessments, particularly those using isokinetic dynamometry, remain central to RTS protocols, but the limitations of LSI highlight the need for more robust metrics. Clinicians should interpret LSI with caution and consider supplementing it with bodyweight-relative strength and pre-injury data, where available. In resource-limited settings, PFD can be a viable alternative to IKD.

Functional tests, including hop and balance, offer valuable insights but often lack specificity for sport demands. Emerging technologies, such as force platforms and 3D motion capture, improve sensitivity to biomechanical deficits, but contain accessibility restrictions, while innovations in agility, CoD and neurocognitive assessments bring greater relevance to sport-specific RTS evaluation.

Finally, psychological readiness plays a critical role in successful RTS, emphasising the need for interventions to address psychological barriers. Routine use of ACL-RSI and IKDC can help clinicians identify athletes needing psychological support.

Collectively, these findings highlight the importance of individualised, multidisciplinary approaches that integrate physical, functional, and psychological considerations. Clinicians should adopt a layered RTS framework incorporating strength benchmarks, sport-specific functional assessments, and psychological screening to optimise outcomes and reduce reinjury risk following ACLR surgery.

**Prelude to Chapter 3**

Chapter 3 presents the second research study in this thesis, a retrospective descriptive analysis of RTS testing outcomes from a clinical cohort of individuals who underwent ACLR. Drawing on data collected at a specialised physiotherapy clinic in Aotearoa NZ, this chapter provides real-world insights into RTS test performance across strength, hop, jump, and psychological domains.

In addition to describing overall pass rates and outcome patterns, the analysis explores associations between test performance and factors such as age, sex, sport type, graft choice, and completion of prehabilitation. The study also considers whether achieving high scores on RTS tests correlates with successful RTS, offering a critical reflection on the utility of current pass thresholds.

As with the previous chapter, this study is presented in the format of a journal article. It is structured to meet the requirements of academic publication in Physical Therapy in Sport and is intended to be read as a self-contained manuscript.

# Chapter 3: A Retrospective Descriptive Analysis of Return to Sport (RTS) Tests Following Anterior Cruciate Ligament Reconstruction (ACLR) Surgery

## 3.1 Abstract

Objective

To describe return to sport (RTS) test performance, associated factors, and sport resumption levels following anterior cruciate ligament reconstruction (ACLR) in a clinical cohort in Aotearoa New Zealand (NZ).

Design

Retrospective descriptive analysis.

Setting

Specialised physiotherapy clinic in Auckland, Aotearoa NZ (KneeCare).

Participants

165 individuals (mean age 28.6 years) who completed RTS testing post-ACLR between July 2021 and January 2025.

Main Outcome Measures

RTS test outcomes (strength, hop, jump, and psychological readiness) and RTS status, and associations between these and demographic and clinical variables.

Results

75% returned to sport, but only 43% resumed pre-injury levels. Horizontal hop tests showed the highest pass rates; strength and vertical jump tests the lowest (<50%). ACL-RSI scores were significantly associated with RTS status ($p < .001$) and were lower in participants with prior ACL injury or lateral tenodesis. BPTB grafts were associated with lower knee extension LSI ($p = .002$) and prehabilitation was linked to better hamstring strength ($p = .007$). High test scores (≥95% LSI) did not consistently predict successful RTS.

Conclusions

Significant functional deficits persist post-ACLR. RTS decisions should incorporate physical, psychological, and contextual factors. An individualised, equitable approach may improve outcomes, especially for underrepresented groups in Aotearoa NZ.

### 3.2 Highlights

1. Only 43% of participants returned to full pre-injury sport levels
2. Highest RTS pass rates were in horizontal hop tests; strength and vertical jump tests had less than 50% pass rates
3. Psychological readiness (ACL-RSI) was significantly associated with RTS success
4. Graft type and prehabilitation influenced knee strength limb symmetry outcomes
5. High RTS test scores did not predict successful RTS
6. RTS decision-making should consider psychological, contextual, and sport-specific factors
7. Culturally responsive care is needed to address inequities after ACL injury in Aotearoa NZ

### 3.3 Introduction

Anterior cruciate ligament (ACL) injuries are common in pivoting and cutting sports such as football (soccer), netball, basketball, and rugby, and have significant physical, psychological, and performance-related consequences for athletes (4, 25, 65). Injury rates are rising (136), particularly among female and younger athletes (18), with incidence rates ranging from 30 to 78 per 100,000 person-years (7). For athletes intending to return to high-risk sport, ACL reconstruction (ACLR) surgery remains the most common treatment pathway (16, 17, 18, 19).

While return to sport (RTS) following ACLR surgery is often used as a key rehabilitation milestone, outcomes remain variable. Although up to 80% of individuals are reported to return to some form of sport (66), fewer than half may return to their previous level of performance, especially in non-elite populations (5, 25, 26). Moreover, returning to sport is associated with a heightened risk of graft or contralateral ACL injury (67, 68), with reported re-injury rates as high as 24% (28).

To support safe and successful RTS, test batteries are commonly used to assess functional recovery. These typically include a combination of strength, hop and jump performance tests, and psychological readiness assessments. While passing RTS criteria has been associated with reduced re-injury risk (4, 6, 46), the lack of standardised test protocols and thresholds has led to wide variability in test selection and reported RTS pass rates, which range from 18% to 88% across studies (27). Despite this variability, there is limited real-world reporting on how RTS testing is being applied in clinical practice.

This study aims to provide a retrospective descriptive analysis of RTS testing outcomes in a large cohort of individuals following ACLR, collected from a specialised physiotherapy clinic (KneeCare) in Aotearoa New Zealand (NZ). The data presented reflects routine, clinically informed decision-making and offers insight into test performance RTS outcomes in a contemporary rehabilitation setting.

Specifically, this study explores the overall RTS test pass rate and the typical time post-surgery at which individuals complete testing. It also examines whether demographic or clinical factors such as age, gender, ethnicity, type of sport, or graft type are associated with RTS test scores or the level of sport resumption. Further, the study investigates what proportion of individuals who pass testing achieve high scores for limb symmetry (≥95%), and whether these high scores are associated with greater rates of return to pre-injury sport participation.

### 3.4 Materials and Methods

#### 3.4.1 Study design and participants

This retrospective study analysed data collected as part of a RTS test battery conducted at a specialised physiotherapy clinic in Auckland, Aotearoa NZ. The study was approved by Auckland University of Technology Ethics Committee (AUTEC; 24/203).

The data collection process, outlined in Figure 1, ranged from July 2021 to January 2025. A total of 172 patients who had sustained an ACL rupture were initially included. Nearly all participants had completed isokinetic strength testing, and the majority also completed single leg hop and jump performance testing as part of the RTS protocol. Inclusion criteria for retrospective analysis were: 1) completion of ACLR surgery, 2) aged 16 years or older, and 3) referral for RTS testing as part of rehabilitation. Patients were excluded if they elected for non-operative rehabilitation. The final sample size for analysis was 165 participants.

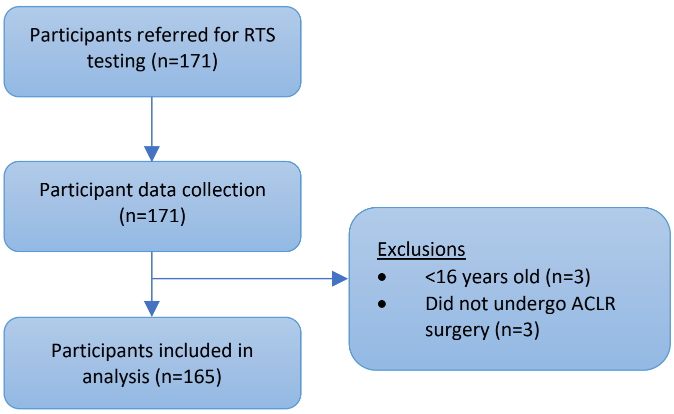


*Figure 3: Data Collection Process*

#### 3.4.2 Data collection

All testing was conducted in a standardised manner by experienced musculoskeletal physiotherapists trained in the RTS protocol as detailed in the section to follow. As the RTS testing process was implemented as a routine quality assurance measure, formal ethics approval was not required. However, all patients provided written informed consent for their data to be used for service evaluation purposes.

Data was collected and stored by the clinical team at KneeCare. Once the data collection period concluded, all identifiable information was removed during the de-identification process conducted by the clinic administrator. De-identified datasets were then securely transferred to the research team via an encrypted cloud-based sharing platform. At no point did the researchers have access to any personally identifiable information, ensuring full participant anonymity throughout the analysis.

As a secondary data collection process, patients who completed RTS testing were subsequently contacted from November 2024 to January 2025 to determine their RTS status. This was carried out by the same clinic through a structured follow-up process: patients were first contacted via email, and if no response was received, a follow-up phone call was made. If there was no response, a final email was sent. A total of 112 participant responses were collected.

### 3.4.3 RTS testing protocol

The RTS testing protocol was developed as a pragmatic, clinically informed quality assurance process to benchmark rehabilitation outcomes and support RTS decision-making (4, 6, 46). The protocol evolved over time in line with best practice guidance, and in response to patient tolerance and feedback from referring orthopaedic surgeons, particularly to avoid flare-ups associated with high-load or unaccustomed jumping tasks.

The test battery included isokinetic strength assessment of the quadriceps and hamstrings using a Biodex System (Biodex Medical Systems Inc., Shirley, NY, USA). Concentric strength was assessed at 90°/s, and the best of three maximal voluntary contractions (MVCs) was used to calculate the limb symmetry index (LSI), defined as (involved limb/uninvolved limb) x 100. Isokinetic strength testing via the Biodex demonstrates excellent test-retest reliability, with reported intraclass correlation coefficients (ICCs) ranging from 0.94 to 0.98 (137).

Functional performance was assessed through a battery of hop and jump tests. Two horizontal hop tests, single leg hop (SLH) and lateral hop (LH), were performed with at least two practice trials followed by three recorded attempts per limb. The best performance for each leg was used to calculate LSI. These hop tests are well established in the literature and have demonstrated good to excellent reliability (SLH ICC = 0.84-0.97, LH ICC = 0.92-1.0) (138, 139).

Vertical jump performance was evaluated using VALD ForceDecks (VALD Performance, Brisbane, Australia) for single leg vertical jump (SLVJ) and single leg drop jump (SLDJ) testing. Participants completed three maximal-effort tests and peak jump height was recorded**.** Jump height was calculated using the flight-time method, the standard ForceDecks algorithm (122, 140). This algorithm uses a projectile-motion equation ($h = gt^2/8$) based on airborne time. Jump height values were subsequently converted to centimetres, then LSI.

The flight-time method assumes fully extended knees at take-off and landing and has demonstrated high reliability when derived from force plate data (122, 140). ForceDecks automatically identified take-off and landing based on vertical ground reaction force thresholds, ensuring consistent event detection across SLVJ and SLDJ trials. ForceDecks are validated systems for assessing jump performance with excellent measurement reliability (ICC > 0.90) (141, 142). All jump-related variables, including jump height (cm), are exported using standardised manufacturer algorithms.

Psychological readiness to RTS was assessed using the ACL-RTS after Injury (ACL-RSI) scale (143). This 12-item questionnaire assesses emotions, confidence, and risk appraisal related to RTS, with scores ranging from 0 to 100. Higher scores indicate greater psychological readiness. The ACL-RSI has demonstrated excellent internal consistency (Cronbach's alpha 0.94) and test-retest reliability (ICC = 0.93) (144).

The criteria for passing individual tests were based on achieving an LSI of ≥90%, which served as the primary clinical benchmark in line with established RTS guidance (4, 46, 108). Not all patients completed every component of the test battery. Variability in test completion was primarily influenced by clinical appropriateness, stage of rehabilitation, pain levels during warm-up or initial testing, familiarity with specific tests, and specific instructions or restrictions from the referring surgeon. Additionally, the RTS protocol evolved over the data collection period, with certain components being introduced or refined at different time points. All testing was conducted within a single session unless clinical needs dictated otherwise.

### 3.5 Statistical Analysis

All statistical analyses were conducted using IBM SPSS Statistics (Version 30). Descriptive statistics were used to summarise participant demographics and clinical characteristics, including mean, standard deviation, frequency, and percentage, shown in Table 6.

Prior to inferential testing, data were examined for statistical assumptions. Normality was assessed using Shapiro-Wilk tests and visual inspection of Q-Q plots and histograms. Homogeneity of variance for parametric analyses was evaluated using Levene's test. Statistical methods were selected based on the distribution of RTS test performance outcomes. For normally distributed measures, one-way analysis of variance (ANOVA) was used to assess differences across categorical variables. Where significant ANOVA results were found, Bonferroni-adjusted post-hoc tests were applied to control for Type I error inflation.

For outcomes not meeting normality or variance assumptions, non-parametric tests were used; Kruskal-Wallis tests for comparisons involving more than two groups, Mann-Whitney U tests for two-group comparisons, and independent-samples median tests where appropriate. Significant Kruskal-Wallis results were followed by Bonferroni-corrected pairwise Mann-Whitney U tests. Associations between RTS test outcomes and continuous variables (e.g., age, height, time since surgery) that were non-normally distributed were analysed using Spearman's rank correlation.

Chi-square tests of independence were employed to explore associations between achieving RTS test thresholds and RTS status. To explore whether higher RTS test performance was associated with superior RTS outcomes in the secondary analysis, test scores were dichotomised into two groups: <95% and ≥95%. Due to low expected cell counts in the initial model, RTS status was re-categorised into three groups: (1) full return to sport, (2) partial return (moderate or low level), and (3) changed sport or did not return. Participants who did not respond, or who responded with 'other' were excluded, resulting in a final sample of 112.

A significance level of $p < .05$ was used for all analyses. Where results were non-significant, null hypotheses were retained and distributional patterns were considered to contextualise findings in relation to RTS outcomes and demographic factors.

*Table 6: Participant Demographics and Clinical Characteristics*

| | **N (%) / Mean (SD)** |
|---|---|
| **Sex** | |
| Male | 120 (72.7%) |
| Female | 45 (27.3%) |
| **Age (years)** | 28.57 (8.82) |
| **Height (cm) mean (SD)** | 176.0 (8.99) |
| **Weight (kg) mean (SD)** | 81.9 (16.16) |
| **Ethnicity** | |
| European | 88 (53.3%) |
| Māori | 18 (10.9%) |
| Asian | 22 (13.3%) |
| Middle Eastern, Latin American and African (MELAA) | 7 (4.2%) |
| Pasifika | 8 (4.8%) |
| Other/Not stated | 22 (13.3%) |
| **Sport at time of injury** | |
| Football (soccer) | 45 (27.3%) |
| Rugby | 42 (25.5%) |
| Basketball | 15 (9.1%) |
| Netball | 14 (8.5%) |
| Martial arts | 5 (3.0%) |
| Snowsports | 4 (2.4%) |
| Motocross | 3 (1.8%) |
| Badminton | 2 (1.2%) |
| Surfing | 2 (1.2%) |
| Other* | 8 (4.8%) |
| Not reported | 25 (15.2%) |
| **Injury mechanism** | |
| Contact | 33 (20.0%) |
| Non-contact | 113 (68.5%) |
| Not reported | 19 (11.5%) |
| **RTS status** | |
| Full return | 48 (29.1%) |

| | |
|---|---|
| Moderate return | 18 (10.9%) |
| Low return | 10 (6.1%) |
| Did not return | 27 (16.4%) |
| Changed sport | 8 (4.8%) |
| Not reported | 54 (32.7%) |
| **Pre-operative rehabilitation** | |
| Yes | 110 (66.7%) |
| No | 54 (32.7%) |
| Not reported | 1 (0.6%) |
| **Graft type** | |
| Hamstring tendon | 109 (66.1%) |
| BPTB | 47 (28.5%) |
| Quadriceps tendon | 9 (5.5%) |
| **Lateral tenodesis performed** | |
| Yes | 34 (20.6%) |
| No | 131 (79.4%) |
| **Previous ipsilateral ACL injury** | |
| Yes | 33 (20.0%) |
| No | 132 (80.0%) |
| **Previous contralateral ACL injury** | |
| Yes | 25 (15.2%) |
| No | 138 (83.6%) |
| Not reported | 2 (1.2%) |
| **Time to surgery (weeks)** | 21.07 (32.85) |
| **Time from surgery to RTS testing (weeks)** | 52.94 (19.06) |

**Other sports: Trampoline, Gaelic football, Cricket, Skateboarding, AFL, Ultimate Frisbee, Athletics, and Hockey (1 participant each)*

### 3.6 Results

3.6.1 Participants

A total of 165 participants were included in the study, with a mean age of 28.57 years (SD 8.82), mean height of 176cm (SD 8.99), and mean weight of 81.9kg (SD 16.16). The sample was predominantly male (72.7%), and the most common ethnic group was European (53.3%), followed by Asian (13.3%), Māori (10.9%), Middle Eastern**,** Latin American and African (MELAA; 4.2%), Pasifika (4.8%), and other or not stated (13.3%).

Football (soccer) and rugby were the most frequently reported sports at the time of injury (27.3% and 25.5%, respectively), with a wide range of other sports also represented. Most injuries occurred during non-contact mechanisms (68.5%). Pre-operative rehabilitation was completed by 66.7% of participants. The most common graft type used for ACLR was hamstring tendon (66.1%), followed by bone-patellar tendon-bone (BPTB; 28.5%), and quadriceps tendon (5.5%). A lateral extra-articular tenodesis was performed in 20.6% of cases. A previous ipsilateral ACL injury was reported by 20% of participants, while 15.2% had sustained a previous contralateral ACL injury.

The median time from injury to surgery was 11.1 weeks (IQR 6.1-17.95), with a mean of 21.07 weeks (SD 32.85). Participants underwent RTS testing at a median of 50.7 weeks (IQR 41.65-58.6) post-operatively, with a mean of 52.94 weeks (SD 19.06). Among the 112 participants who reported their RTS status, 42.9% returned to full participation in their original sport, 16.1% returned to moderate levels, and 8.9% returned to low levels. One in four participants (25%) were unable to return to their previous sport, while 7.1% chose to transition to a different sport.

3.6.2 RTS test outcomes

The primary outcomes were the proportion of participants passing each RTS test (LSI ≥ 90%), and associations between demographic/clinical variables and RTS test performance and RTS status. RTS test outcomes and overall pass rates are shown in Table 2.

*Table 7: RTS Test Outcomes and Pass Rates*

| Outcome Measure | Mean (SD) | Valid | Passed | Pass Rate (%) |
|---|---|---|---|---|
| **Single Leg Hop (SLH)** | | | | |
| Affected limb (cm) | 110.03 (27.45) | — | — | — |
| Unaffected limb (cm) | 115.36 (25.28) | — | — | — |
| LSI (%) | 95.10 (10.10) | 132 | 102 | 77.3% |
| **Lateral Hop (LH)** | | — | — | — |
| Affected limb (n) | 42.90 (15.89) | — | — | — |
| Unaffected limb (n) | 45.35 (15.01) | — | — | — |
| LSI (%) | 93.84 (14.41) | 108 | 72 | 66.7% |
| **Single Leg Vertical Jump (SLVJ)** | | | | |
| Affected limb (cm) | 13.12 (4.63) | — | — | — |
| Unaffected limb (cm) | 15.09 (4.71) | — | — | — |
| LSI (%) | 86.86 (14.93) | 109 | 53 | 48.6% |
| **Single Leg Drop Jump (SLDJ)** | | | | |
| Affected limb (cm) | 14.45 (5.21) | — | — | — |
| Unaffected limb (cm) | 16.42 (5.23) | — | — | — |
| LSI (%) | 88.14 (15.30) | 59 | 27 | 45.8% |
| **Knee Extension Peak Torque 90°/s** | | | | |
| Affected limb (Nm) | 191.58 (55.09) | — | — | — |
| Unaffected limb (Nm) | 221.22 (57.53) | — | — | — |
| LSI (%) | 86.88 (12.07) | 163 | 79 | 48.5% |
| **Knee Flexion Peak Torque 90°/s** | | | | |
| Affected limb (Nm) | 97.81 (29.56) | — | — | — |
| Unaffected limb (Nm) | 106.71 (28.46) | — | — | — |
| LSI (%) | 91.63 (12.24) | 163 | 96 | 58.9% |
| **Psychological Readiness** | | | | |
| ACL-RSI | 60 (22) | — | — | — |

There were no significant associations between RTS test performance and demographic variables such as age, height, weight, ethnicity, time from surgery to testing, or type of sport played.

Several significant associations were observed between ACL-RSI scores and RTS status. Participants who chose to transition to a different sport reported the highest psychological readiness (median = 80, IQR = 48-92), followed closely by those who returned to full participation in sport (median = 72, IQR = 53-87). In contrast, markedly lower scores were observed in those who returned to low levels of sport (median = 39, IQR = 28-51) and those unable to return to their previous level (median = 48, IQR = 35-60). Between-group differences were statistically significant (Fig 4. Kruskal-Wallis, $p < .001$; Fig 5. Median Test, $p = .013$).

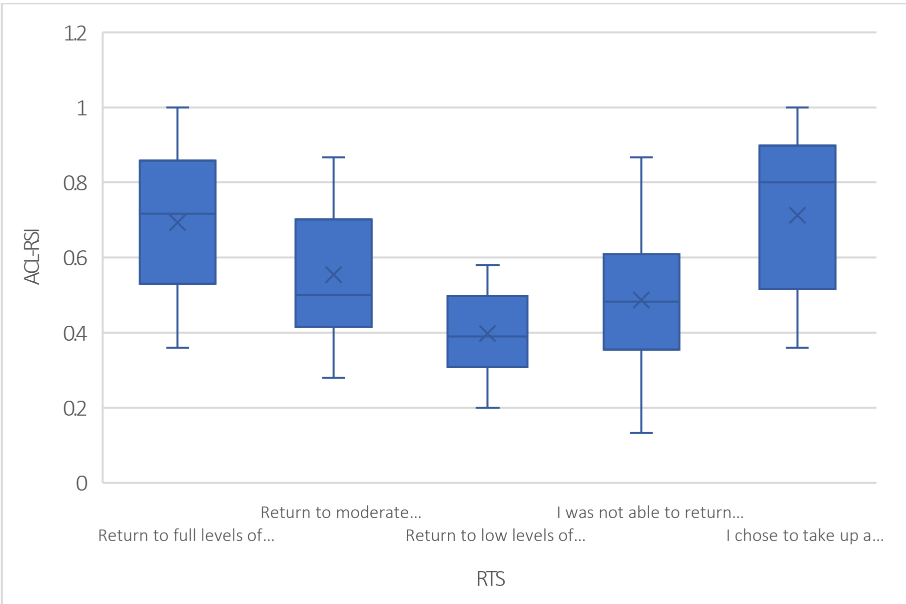


*Figure 4: Independent-Samples Kruskal-Wallis Test for Associations Between ACL-RSI and RTS Status*

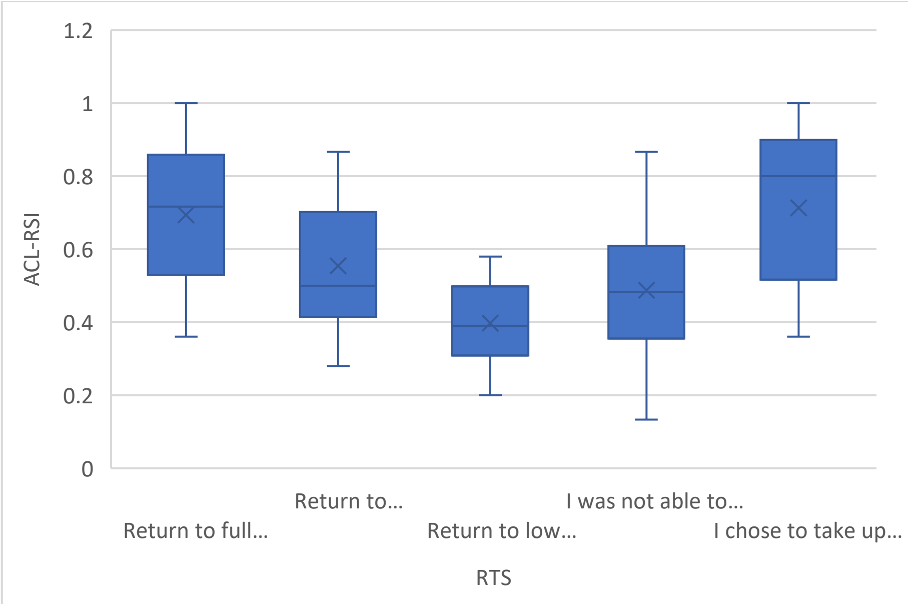


*Figure 5: Independent-Samples Median Test for Associations Between ACL-RSI and RTS Status*

Participants with a history of previous ipsilateral ACL injury reported significantly lower psychological readiness, with a median ACL-RSI score of 47 (IQR = 35-68), compared to those without prior injury (median = 60, IQR = 45-83; Fig 6. Mann-Whitney U, *p* = .024). Similarly, those who had undergone a lateral tenodesis procedure also demonstrated lower ACL-RSI scores (median = 48, IQR = 35-70) than those who had not (median = 60, IQR = 45-83; Fig 7. *p* = .019).

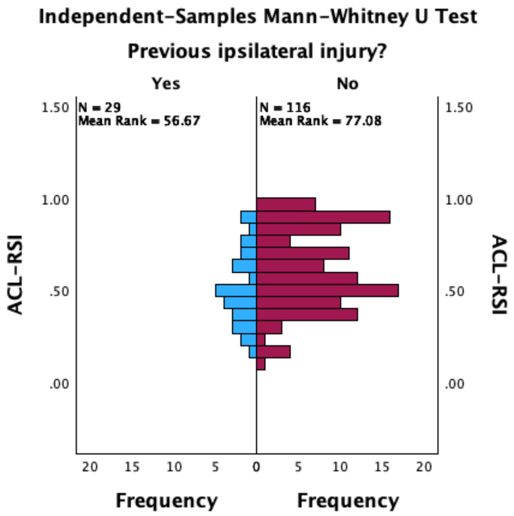


*Figure 6: Independent Samples Mann-Whitney U Test for Associations Between ACL-RSI and Previous Ipsilateral Injuries*

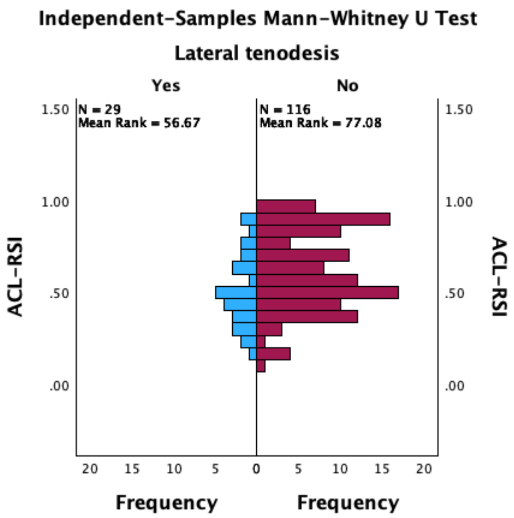


*Figure 7: Independent Samples Mann-Whitney U Test for Associations Between ACL-RSI and Lateral Tenodesis*

Furthermore, graft type was significantly associated with knee extension strength. Participants with BPTB grafts demonstrated significantly lower knee extension LSI scores (median = 84.4%) compared to those with hamstring tendon grafts (median = 90.8%; Fig 8. Kruskal-Wallis, $p$ = .002). Although the quadriceps tendon group had a comparable median LSI (85.8%), pairwise comparisons indicated that only the BPTB vs hamstring group difference reached statistical significance ($p$ = .030, Bonferroni-adjusted).

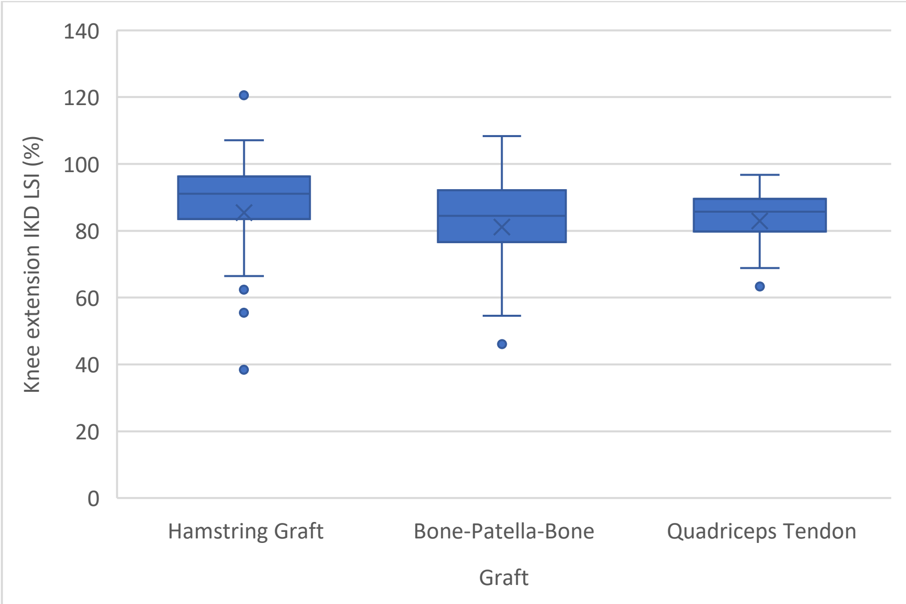


*Figure 8: Independent-Samples Kruskal-Wallis Test for Associations Between Graft Type and Knee Extension Strength*

Although differences in knee flexion strength symmetry between graft types were not statistically significant (Fig 9. Median Test, $p$ = .275; Fig 10. Kruskal-Wallis, $p$ = .105), a trend was observed whereby participants with BPTB grafts exhibited higher flexion LSI scores (median = 95.88, IQR = 85.43-104.99) compared to those with hamstring tendon grafts (median = 90.91, IQR = 83.04-97.97) and quadriceps tendon grafts (median = 90.37, IQR = 81.72-95.56).

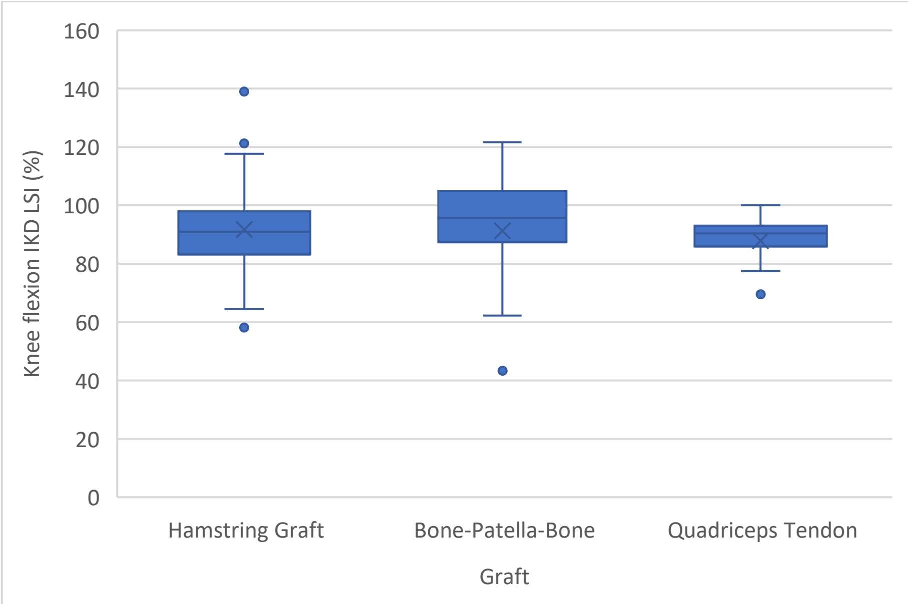


*Figure 9: Independent Median Test for Associations Between Graft Type and Knee Flexion Strength*

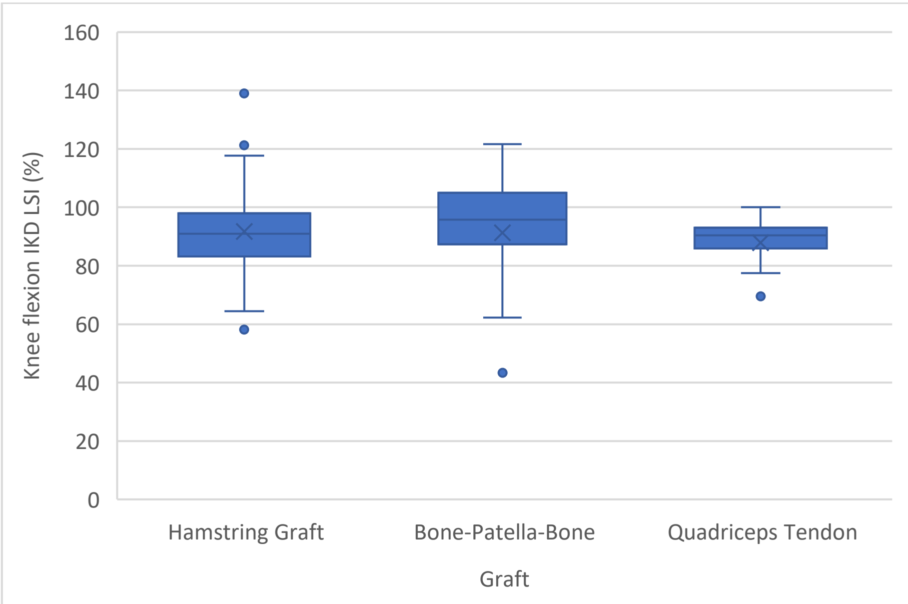


*Figure 10: Independent-Samples Kruskal-Wallis Test for Associations Between Graft Type and Knee Flexion Strength*

Limb symmetry in the lateral hop (LH LSI) differed significantly across RTS groups (Fig 11. Kruskal–Wallis, $p$ = .041). Participants who returned to full participation in sport demonstrated the highest median LH LSI (100, IQR = 95.5-102.9), while those who returned to moderate levels had slightly lower scores (median = 97.2, IQR = 87.6-102.9). In contrast, those who returned to low levels of sport participation (median = 88.9, IQR = 82.0-93.0), those who were unable to return to their previous sport (median = 92.3, IQR = 80.4-104.2), and those who chose to take up a different sport (median = 90.1, IQR = 74.2-100) had generally lower LSI scores.

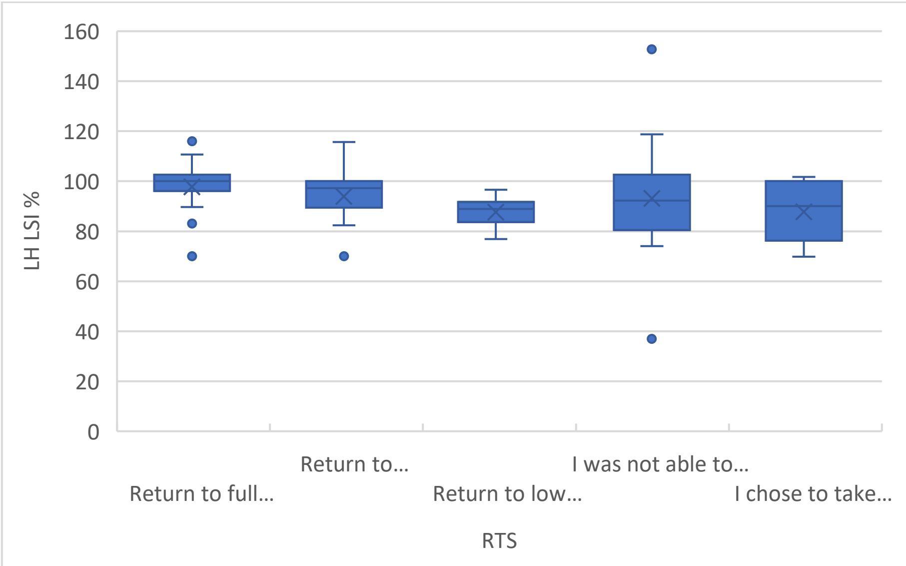


*Figure 11: Independent-Samples Kruskal-Wallis Test for Associations Between Lateral Hop Test and Return to Sport Status*

Furthermore, engagement in prehabilitation prior to surgery was associated with higher knee flexion strength symmetry. Participants who completed prehabilitation demonstrated a higher median IKD flexion LSI (94.1, IQR = 86.6-101.0) compared to those who did not (median = 89.5, IQR = 79.7-96.2). This difference was statistically significant, as indicated by both the Median Test ($p$ = .019; Fig 12) and the Mann-Whitney U test ($p$ = .007; Fig 13).

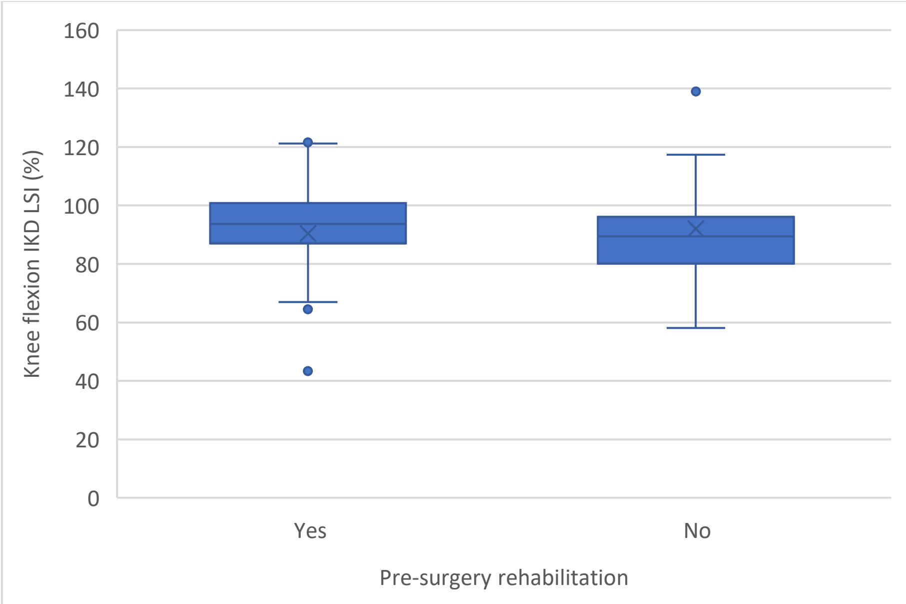


*Figure 12: Independent Median Test for Associations Between Prehabilitation and Knee Flexion Strength*

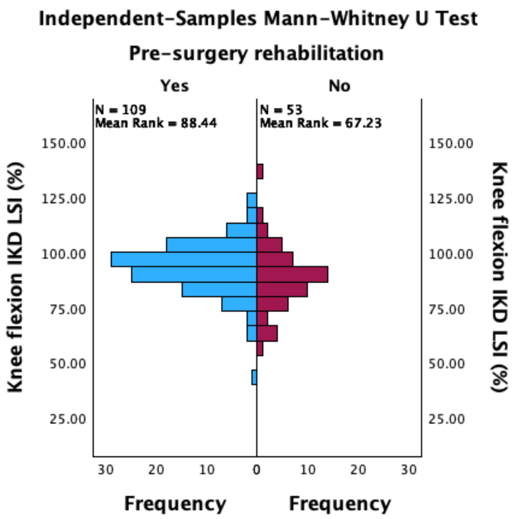


*Figure 13: Independent-Samples Kruskal-Wallis Test for Associations Between Prehabilitation and Knee Flexion Strength*

In the secondary analysis results (Appendix C and D), no statistically significant associations were found between high RTS test scores (≥95%) and RTS outcomes. For example, cross-tabulation (Appendix K) showed that among participants with knee extension LSI scores ≥95%, 30.4% achieved full return to sport, 43.5% returned partially, and 26.1% changed or ceased sport participation. In contrast, those with LSI scores <95% had a higher proportion achieving full return (46%) and a similar proportion returning partially (20.7%).

### 3.7 Discussion

3.7.1 Pass rates and RTS status

This study investigated RTS test outcomes following ACLR surgery in a clinical cohort from Aotearoa NZ. The results demonstrate considerable variability in performance across individual tests and highlight several factors associated with test outcomes.

Overall, 75% of participants who reported their RTS status returned to some form of sport, though only 43% returned to full participation in their original sport. Fewer than half returned to their previous level of sport, findings consistent with existing literature indicating that many athletes fail to regain pre-injury levels of sport participation or performance (25, 26, 145). Across the RTS tests, the highest pass rate was observed in the SLH test (77%), while strength and vertical jump performance measures had substantially lower pass rates (less than 50%). These findings highlight persistent functional deficits even at a mean of 12 months after surgery and reflect ongoing challenges in regaining symmetry in key neuromuscular domains. Earlier restoration of horizontal hop test symmetry relative to quadriceps strength aligns with prior research (4) and reinforces the understanding that limb symmetry may recover differentially depending on the type of task assessed.

3.7.2 Demographics and Clinical Characteristics

No significant associations were found between test performance and demographic variables such as height, weight, age, or sport type. There were also no significant associations between ethnicity and test or RTS outcomes. However, this study's findings offer an opportunity to contextualise our data within broader national patterns of ACL injury incidence. According to a recent study by Pryymachenko, Wilson (136) et al., Pacific peoples had the highest age- and sex-adjusted cruciate ligament (CL) injury incidence rates in Aotearoa NZ (214 per 100,000), followed by Europeans (187), Māori (182), and Asians (108). Despite this, Māori and Pasifika individuals together represented only around 15% of our surgical cohort. While they experience disproportionately high injury rates, they appear under-represented in our surgical cohort.

Several factors might explain these observations. Firstly, differences in sport participation partly underpin the higher CL injury incidence among Māori and Pasifika; national surveys show Pasifika have high participation in sports linked to ACL injuries, while Asian populations have the lowest activity levels (146). However, socioeconomic barriers and healthcare access inequities may reduce the likelihood of receiving surgical intervention or access to rehabilitation services among these populations (147, 148).

Nearly 70% of ACL injuries in this cohort were reported as non-contact in nature, aligning with wider literature that show most ACL ruptures occur during deceleration, pivoting, or cutting movements (54, 120, 128). This reinforces the importance of evaluating neuromuscular control during deceleration in landing and CoD tasks in RTS testing, given these mechanisms are primary drivers of injury (3, 7, 9, 10). RTS batteries that fail to include CoD or agility assessments may miss critical deficits. Only a minority of studies incorporate CoD or reactive agility testing (1) despite their potential to better mimic sport-specific loads and decision-making (46, 100). Incorporating such tests may enhance the ecological validity of RTS decisions.

#### 3.7.3 Test performance and RTS outcomes

Psychological readiness, measured via the ACL-RSI, was significantly associated with RTS status. Those who had returned to pre-injury sport participation reported higher ACL-RSI scores than those who returned partially ($p < .001$), although scores in the changed sport group were similar to the full RTS group. This suggests psychological readiness is not strictly linear and may be influenced by factors beyond injury recovery. ACL-RSI scores were also significantly lower in individuals with previous ipsilateral ACL injury and those who had undergone a lateral tenodesis procedure, suggesting these groups may carry greater psychological burden or perceived vulnerability, factors that should be considered when making RTS decisions.

Graft type influenced outcomes in strength testing. Participants with BPTB grafts exhibited lower LSI in knee extension compared to those with hamstring or quadricep tendon grafts ($p = .002$), consistent with previous research highlighting quadriceps morbidity and anterior knee pain associated with BPTB grafts (149, 150). Conversely, knee flexion symmetry was slightly higher in those with BPTB grafts, although this trend did not reach significance. This aligns with expectations, as hamstring grafts typically involve harvesting semitendinosus and/or gracilis, which may transiently impair flexor strength (151, 152).

Further, prehabilitation was positively associated with knee flexion strength symmetry, with significantly higher LSI values in those who completed pre-operative rehabilitation ($p = .007$). This supports existing evidence for the benefits of early neuromuscular loading after injury in optimising postoperative recovery (153), although this effect was not observed across all test domains.

Interestingly, high performance on RTS tests was not significantly associated with successful RTS. In the secondary analysis, achieving ≥95% LSI in knee extension strength did not predict full RTS, and in some cases, participants with lower LSI demonstrated better RTS outcomes. This challenges the assumption that "passing" RTS tests directly translates to readiness or performance and highlights the limitations of relying solely on test thresholds to guide return decisions.

Several factors may explain these findings. Psychological readiness, particularly confidence and fear of re-injury, strongly influences return behaviour and often predicts RTS more accurately than strength or hop symmetry (132, 135). External factors such as team selection, level of competition, time demands, and personal priorities may also prevent RTS even when physical criteria are met (5, 154). Conversely, some athletes return despite failing physical tests due to motivation or competitive pressures (94, 130). As a result, physical test thresholds represent only one part of the recovery profile and may not capture real-world barriers or facilitators of return. This reinforces the need for a multifactorial approach that incorporates physical performance, psychological readiness, contextual factors, and athlete goals.

Furthermore, the limitations of LSI as a criterion were further evident in this cohort, where high symmetry in strength, hop, or jump tasks did not consistently correlate with sport resumption. Concerns have been raised that LSI may overestimate recovery due to bilateral deficits or contralateral deconditioning following ACLR (111, 112, 113). Supporting this, our isokinetic data showed mean peak torque values of 2.3 Nm/kg on the involved limb and 2.6 Nm/kg on the uninvolved limb, both below the ≥3.0 Nm/kg benchmark commonly cited for athletic populations (81, 155). These results suggest that even the unaffected limb may be underperforming, and achieving >90% LSI may not reflect true recovery when both limbs are suboptimal.

Low absolute quadriceps strength has been associated with poorer functional outcomes (156, 157). In this context, the below-threshold torque values observed in our cohort may represent a clinically meaningful deficit, even when symmetry appears acceptable. This supports the inclusion of absolute, bodyweight-adjusted benchmarks in RTS decision-making, particularly for athletes returning to high-risk sports. Consequently, RTS test batteries should consider including absolute strength thresholds, such as ≥3.0 Nm/kg to ensure minimum performance standards are met, rather than relying solely on interlimb comparisons.

In summary, this study confirms that RTS testing remains a useful but incomplete tool in guiding RTS decisions after ACLR. Many participants demonstrated significant functional deficits at 12 months post-surgery, particularly in strength-based tasks, and superior test performance was not reliably associated with RTS outcomes. These results support a broader approach to RTS decision-making, incorporating both quantitative and contextual elements to better reflect real-world sport demands and recovery trajectories. This is consistent with findings from our previous scoping review, which identified a lack of standardisation and considerable variability in RTS protocols (1), alongside concerns that commonly used tests may insufficiently replicate the demands of pivoting sports.

Future rehabilitation frameworks should thus embrace a multifactorial approach, integrating psychological readiness, contextual considerations, and on-field reactive or dual-task assessments that more closely replicate sport demands. This is particularly pertinent in Aotearoa NZ, given the high injury burden among Māori and Pasifika populations, necessitating culturally responsive care pathways and equitable access to orthopaedic care and advanced rehabilitation services.

### 3.8 Strengths and Limitations

This study has several strengths. First, it utilised validated and clinically relevant RTS assessments, including hop and jump tests, isokinetic strength tests, and the ACL-RSI scale, enhancing the methodological rigour and applicability of findings to real-world practice. Second, data were drawn from a heterogeneous clinical cohort, providing insights into post-ACLR recovery across a diverse population and increasing the external validity of the results. Third, the inclusion of both physical and psychological measures supports a multifactorial understanding of RTS readiness. Fourth, the reporting of participant ethnicity and demographic characteristics allowed for preliminary consideration of equity and access issues within the surgical cohort, particularly with respect to Māori and Pasifika populations. Finally, detailed reporting of the time from injury to surgery and timing of RTS testing permits contextual interpretation of outcomes within typical clinical timelines.

However, several limitations should be noted. Although the overall sample size was moderate (n = 165), several subgroup analyses involved smaller numbers, reducing statistical power and increasing the risk of Type II error. Furthermore, RTS status was self-reported by only a subset of participants (n = 112), which may introduce response bias and limit the generalisability of the findings. Some RTS test data were non-normally distributed and demonstrated ceiling effects, which may have constrained the ability to detect subtle but clinically meaningful differences between groups. Additionally, the cross-sectional design restricts causal inference and precludes the assessment of functional progression or long-term RTS outcomes over time. Lastly, rehabilitation variables such as programme content, duration, and adherence were not standardised or controlled for, and may have influenced both performance outcomes and RTS status.

### 3.9 Conclusion

This study highlights the complex, multifactorial nature of returning to sport following ACLR surgery in a diverse cohort. Although most participants returned to some level of sport after ACLR surgery, fewer than half regained their pre-injury level of participation, with persistent deficits especially in strength and vertical jump tasks. Psychological readiness, graft type, previous injury history, and engagement in prehabilitation were all associated with functional and RTS outcomes, underscoring the interplay of physical and psychological factors in recovery. Notably, performance on RTS tests did not consistently translate to successful RTS outcomes, challenging reliance on isolated pass thresholds.

These findings reinforce the need for an individualised approach to RTS decision-making that integrates quantitative test results with psychological readiness, contextual demands, and culturally responsive care, particularly important in addressing inequities among Māori and Pasifika populations. Future work should explore longitudinal trajectories and incorporate more sport-specific assessments to better guide safe and effective RTS.

## Chapter 4: Discussion and Conclusions

This chapter discusses the findings of the thesis in relation to its overarching aims: to investigate the application, outcomes, and current best practice surrounding RTS testing following ACLR surgery. By combining a scoping review of the literature with a retrospective analysis of clinical outcomes in Aotearoa NZ, this research provides insight into both the theoretical foundations of RTS testing and its practical implementation in real-world physiotherapy settings.

The discussion is organised around the thesis research questions, beginning with an examination of current best practice for RTS assessment and the variability that exists across protocols. The chapter then considers clinical outcomes from the retrospective analysis, including pass rates, the timing of RTS testing, and associations with demographic and clinical variables. The achievement of high-test performance thresholds is evaluated in relation to RTS outcomes, highlighting the predictive value and limitations of current criteria.

In addition, broader themes are explored, including the utilisation of psychological readiness measures, the limited incorporation of sport-specific assessments, and the influence of prehabilitation, rehabilitation and integrated care models. The chapter also addresses the strengths and limitations of the thesis, before outlining clinical implications and key directions for future research.

Collectively, this discussion seeks to situate the findings of the thesis within the wider body of RTS after ACLR research and clinical practice, identifying where progress has been made and where further refinement is required to support safer, more effective RTS decision-making.

### 4.1 Summary of Main Findings

#### 4.1.1 Variability in RTS Testing Protocols, Timing and Pass Rates

This thesis demonstrated that variability in RTS protocols remains a significant challenge in ACL rehabilitation. The scoping review demonstrated that although strength and hop tests dominate, the specific selection of measures, the order of testing, and the definition of "pass" criteria vary markedly. For example, some studies relied only on horizontal hop tests, quadricep strength MVIC symmetry, and a PROM, while others incorporated isokinetic strength of quadriceps and hamstrings, hamstring-to-quadricep strength ratios (H:Q), vertical jump performance, horizontal hop performance, PROM's, *and* agility/CoD tests. This heterogeneity not only reflects the absence of a universally accepted RTS framework but also limits comparability across studies and reduces the external validity of RTS outcomes reported in the literature. Despite increasing recognition of the need for multidomain assessment, implementation is often pragmatic and shaped by time, resources, and clinician preference rather than standardised guidelines (108). This suggests that RTS testing may be influenced as much by contextual constraints as by evidence-based consensus, which may partially explain the variability in reported reinjury and return rates across cohorts.

Variability also extended to the timing of RTS assessments. In the clinical cohort assessed in this thesis, athletes were typically tested beyond the widely recommended nine-month postoperative timeframe, with most assessed after 12 months. Despite this extended period, a large proportion continued to demonstrate persistent strength and jump asymmetries (<50%). This finding challenges the assumption that prolonged rehabilitation duration alone ensures restoration of functional symmetry. It raises important questions about whether current rehabilitation approaches are sufficient to restore symmetry and whether periodic interim assessments might provide opportunities to identify and address deficits earlier. Prospective research supports this shift; Grindem, Snyder-Mackler (4) suggest that time should serve as a minimum safety threshold rather than the primary clearance criterion, while Bodkin, Bruce (158) and Kotsifaki, Korakakis (20) have shown that structured interim testing at six week intervals or at three, six, and nine months post-surgery facilitates progressive monitoring, supports criteria-based progression, improves strength recovery, and may allow more informed RTS decisions in selected populations rather than uniformly delaying clearance beyond arbitrary time points (159).

The pass rates observed in this thesis mirror the challenges reported internationally. Less than half of participants achieved the commonly cited ≥90% LSI threshold for strength and jump tests, and very few reached the higher benchmark. When all RTS domains were considered collectively, pass rates were low, echoing findings from large-scale cohorts where as few as 20% of athletes achieved RTS test battery pass thresholds (46, 108, 160, 161, 162). Importantly, this convergence across independent datasets suggests that low pass rates may not reflect local rehabilitation shortcomings, but rather inherent difficulty in achieving stringent symmetry-based criteria. The discrepancy between prolonged rehabilitation durations and modest pass rates highlights the difficulty of achieving stringent thresholds for some athletes and raises questions regarding whether these benchmarks are universally realistic or clinically meaningful.

Taken together, these findings highlight two critical points. First, time alone is insufficient as a determinant of readiness, and RTS assessment should be restructured as a continuum of repeated, criteria-based checkpoints rather than single end-stage evaluations. Second, current pass thresholds remain challenging to achieve for some people, even with extended rehabilitation, suggesting that future work should explore more individualised and context-sensitive benchmarks that balance safety with feasibility. Such an approach may better accommodate individual variability in recovery trajectories while preserving the protective intent of RTS criteria.

#### 4.1.2 Association Between Demographical or Clinical Factors and RTS Test Performance

A range of clinical characteristics have been explored in the literature as potential determinants of RTS outcomes following ACLR. Within this thesis, prehabilitation emerged as one factor significantly associated with improved test performance, specifically in knee flexion strength. This finding aligns with growing evidence that targeted prehabilitation enhances post-operative recovery (153, 163, 164). However, it remains unclear whether this association reflects the physiological benefits of early neuromuscular loading, greater patient engagement, or pre-existing differences in motivation and baseline capacity among those who elect to undertake prehabilitation.

Knee flexion strength is particularly relevant given its role in dynamic stability and ACL loading, though findings in relation to hamstring strength and its relationship with reduced ACL injury risk are more variable (4). This variability suggests that hamstring strength symmetry alone may not directly translate to protective neuromechanics, but rather represents one component within a broader kinetic chain contribution to joint stability.

Conversely, quadriceps strength is consistently highlighted as a key factor for ACLR rehabilitation success, with stronger quadriceps pre- and post-surgery linked to improved long-term function and enhanced RTS rates (153, 165, 166). Interestingly, knee extension strength outcomes in the clinical cohort assessed were less affected, suggesting that prehabilitation programmes in this setting may not have adequately targeted quadriceps strength. Alternatively, this may reflect the persistent influence of AMI, which can limit voluntary quadriceps activation despite progressive loading (48). Given that stronger pre-operative quadriceps are linked to superior long-term outcomes (153, 165, 166), future prehabilitation approaches may need to place greater emphasis on quadriceps-focused loading while concurrently addressing neuromuscular inhibition mechanisms rather than strength deficits alone.

Surgical variables such as graft type have also been associated with differential recovery profiles. ACLR surgery is typically performed using either a BPTB or HT autograft. BPTB autografts are often linked to greater mechanical stability but may result in anterior knee pain and quadriceps weakness (149, 150), whereas HT autografts can leave residual deficits in knee flexion strength (151, 152). Alternative autologous grafts, such as QT autografts, are becoming increasingly popular (167, 168), however these can lead to early quadriceps weakness, extensor inhibition, and anterior knee discomfort (169, 170). These graft-specific sequelae can directly impact test performance, especially in strength assessments. Importantly, such physiological trade-offs highlight that graft selection may influence short- to medium-term test symmetry without necessarily dictating long-term functional capacity or reinjury risk.

In the clinical cohort investigated in this study, graft type did influence RTS test performance. Participants with BPTB grafts demonstrated significantly lower knee extension strength LSI compared with other graft choices, consistent with evidence of donor-site morbidity and persistent quadriceps deficits following BPTB harvest (149, 150). While statistically significant, the clinical magnitude of this difference should be interpreted cautiously, as LSI may underestimate bilateral weakness and does not capture absolute strength capacity. Nevertheless, these findings suggest the importance of tailoring rehabilitation strategies to graft-specific limitations, ensuring that deficits specific to the graft site are addressed in both early and late-stage rehabilitation.

Demographical factors, such as sport type, are important considerations for RTS assessment following an ACLR. Athletes returning to pivoting and cutting sports such as football, netball, and rugby face substantially higher reinjury risk compared with those in endurance or non-pivoting sports (26). These sports require frequent deceleration, directional changes, and reactive movements that place high multiplanar loads on the knee joint, challenging graft integrity and neuromuscular control even in athletes who meet RTS benchmarks (171). As such, meeting RTS benchmarks does not necessarily imply restoration of sport-specific neuromechanical competence, particularly under reactive and unpredictable conditions.

Demographic characteristics including age and sex are also relevant. Female athletes sustain ACL injuries at higher rates than males (172) and demonstrate neuromuscular control patterns, such as increased valgus moments, that may influence rehabilitation progression and testing outcomes (172, 173). They also tend to experience slower quadriceps strength recovery, worse self-reported function, and lower RTS rates following ACLR compared with males (174, 175). These sex-specific disparities in recovery may be influenced by hormonal, anatomical, and sociocultural factors that are rarely addressed in standard rehabilitation protocols.

Younger athletes are also consistently identified as being at higher risk of injury, particularly graft rupture and contralateral ACL injury, with risk decreasing progressively with age (13, 171). This may reflect higher exposure to high-risk pivoting sports, greater participation intensity, and a tendency to RTS before full neuromuscular recovery. Conversely, older athletes may demonstrate lower reinjury risk but slower strength recovery and longer rehabilitation timelines (154). These age-related patterns suggest that while youth may confer physical advantages for rehabilitation progression, it also increases behavioural and exposure-related risk, reinforcing the need for ongoing neuromuscular and psychological readiness monitoring before RTS clearance.

Nevertheless, demographic variables such as age, sex and sport type did not show significant associations with RTS test outcomes in the clinical cohort assessed in this thesis. Whilst several studies have linked younger age, female sex, and HT grafts to higher reinjury rates (12, 13, 176), these findings suggest that these characteristics are less predictive of achieving RTS test benchmarks in the short to medium term. This distinction is important, as predictors of reinjury may not align with predictors of test performance, highlighting the conceptual difference between passing a test battery and achieving safe long-term return.

On the other hand, psychological readiness was a factor strongly associated with RTS success. Lower ACL-RSI scores were observed in those with prior ACL injury or who had undergone a lateral tenodesis procedure. This finding highlights the lasting psychological impact of previous injury experiences and complex surgical histories and underscores the need to integrate psychological support throughout rehabilitation. It also echoes existing evidence that fear of reinjury and reduced confidence are key barriers to successful RTS (25, 85, 132, 135).

Ethnicity and cultural context, although less frequently studied, are also likely to play a role. In Aotearoa NZ, Māori and Pasifika athletes experience disproportionate cruciate ligament injury rates yet remain underrepresented in the evidence base (19, 136). While this thesis found no significant associations between ethnicity and RTS test performance or RTS outcomes, it is likely that broader social determinants of health, such as access to specialised rehabilitation, socioeconomic constraints, and culturally responsive care, affect recovery trajectories and engagement with testing processes. These inequities reflect a wider pattern across musculoskeletal and sports medicine in which Māori and Pasifika populations face structural barriers to care continuity, follow-up, and culturally safe rehabilitation environments (177). The absence of statistical association in this cohort should therefore not be interpreted as absence of inequity, but rather as a limitation of sample size and study design in detecting complex systemic influences.

Taken together, these findings indicate that modifiable, clinically driven factors may play a more immediate role in influencing RTS test performance than demographic characteristics. However, this interpretation should be framed cautiously, as demographic influences may manifest more strongly in reinjury incidence and long-term participation rather than short-term test symmetry outcomes.

#### 4.1.3 Predictive Value of RTS Tests and the Role of Psychological Measures

Across the literature, the predictive value of current RTS test batteries for successful return to pre-injury sport has been questioned extensively (6, 47, 108, 161, 178). Although several protocols have been developed to provide objective criteria for safe progression and to reduce reinjury risk, evidence suggests they are imperfect predictors of who will achieve a full and sustained return. For instance, Grindem, Snyder-Mackler (4) and Kyritsis, Bahr (46) demonstrated that failing to meet composite RTS criteria substantially increases reinjury risk, yet passing does not reliably guarantee safe or sustained participation. This asymmetry in predictive value indicates that current RTS batteries may function more effectively as screening tools for elevated risk than as confirmatory indicators of readiness. Meta-analyses have reinforced this, Losciale, Zdeb (161) concluded that ≥90% LSI thresholds in hop, jump or strength tests function better as markers of who is not ready rather than as reliable predictors of long-term success.

Recent evidence reinforces these limitations. Hamrin Senorski, Piussi (179) critically re-examined the use of LSI-based cut-offs and found that neither incremental nor categorical LSI values could distinguish between athletes who safely returned to sport and those who reinjured. Higher LSI scores were sometimes associated with greater reinjury risk, likely reflecting earlier exposure to high intensity play among athletes who progressed faster through rehabilitation. This paradox highlights the risk of equating symmetry with safety, particularly where early clearance may increase cumulative exposure rather than reflect true biomechanical restoration. These findings challenge the validity of symmetry-based thresholds as a surrogate for safe readiness and further highlight the multifactorial nature of RTS outcomes.

Research also indicates that physical performance explains only a small fraction of variance in RTS outcomes (25). Ardern, Taylor (25) showed that contextual and psychological factors often exert stronger effects, with low confidence, fear of reinjury, and emotional responses being consistently linked to delayed or failed RTS (68, 80). Similarly, Langford, Webster (180) reported that meeting physical test thresholds did not consistently translate into competitive return, findings that point toward the limited discriminative value of current test batteries when used in isolation.

In contrast, psychological readiness appeared to be more strongly associated with successful RTS than individual physical variables. Validated PROM's, such as the ACL-RSI and the International Knee Documentation Committee (IKDC) subjective knee form, capture levels of confidence, motivation, and reinjury-related fear, which are not addressed by physical tests (132, 181). Despite this evidence, psychological assessment remains underutilised in practice. A recent survey of physiotherapists in Aotearoa NZ reported that only a minority routinely incorporate psychological readiness measures into RTS decision-making (35). Furthermore, even when these tools are applied in research, threshold values for clearance are seldom defined or standardised, limiting their comparability and clinical applicability (1).

Findings from this thesis align with this wider body of evidence. Within the clinical cohort in this study, achieving ≥90% across strength, jump and hop domains did not strongly predict return to pre-injury sport level. Some athletes successfully returned despite sub-threshold scores, while others who met high symmetry benchmarks did not. In contrast, psychological readiness, as measured by the ACL-RSI, and clinical variables such as surgical complexity or prior ACL injury, appeared more influential in shaping RTS trajectories. While causality cannot be inferred from this observational dataset, the strength and consistency of association between ACL-RSI and RTS status suggest that psychological factors may play a central role in return behaviour. Some athletes may return successfully despite residual physical deficits if they are psychologically resilient, while others with excellent physical recovery withdraw due to low confidence or fear of reinjury.

Previous research has proposed thresholds for psychological readiness to help guide RTS decision-making. For example, ACL-RSI scores of approximately 60 and 75 have been cited as indicative of readiness for return to participation and full competitive return, respectively. Ardern, Taylor (132) reported mean ACL-RSI scores near 60 ± 22 in athletes who resumed some level of sport, while Webster and Feller (182) found that values above 70-80 were associated with successful competitive RTS. These findings suggest that an ACL-RSI ≥60 reflects sufficient confidence for controlled or modified participation, whereas scores ≥75 align with the psychological readiness typically observed in athletes achieving full RTS in higher risk sport. However, these thresholds should be interpreted as probabilistic rather than deterministic cut-offs, as psychological readiness likely exists along a continuum rather than a binary state.

The distribution of ACL-RSI scores within the clinical cohort examined in this thesis further supports the thresholds proposed in the wider literature (132, 182). Athletes who achieved a full return to their pre-injury sport had median ACL-RSI scores of 71.7 (IQR 53-86.7). In contrast, those with only a moderate return or who were unable to return recorded substantially lower median values (50 and 47.5, respectively). Athletes who transitioned to a different sport demonstrated similar readiness levels to the return to pre-injury level group (median 80). These findings suggest that athletes reaching ACL-RSI scores around 70 to 75 may demonstrate psychological characteristics consistent with readiness for full competitive return, whereas scores in the 50 to 60 range appear consistent with a partial return.

Taken together, both the literature and the current findings from the clinical cohort studied in this thesis suggest that rigid LSI cut-offs risk false positives (clearing athletes who are not fully prepared) and false negatives (restricting those who could succeed despite asymmetries). Current RTS tests therefore seem more effective at identifying those at elevated risk when criteria are not met than at confirming readiness when they are. These limitations highlight the need for more nuanced, multidomain frameworks that integrate physical, psychological, sport-specific, and contextual factors, providing a more ecologically valid and athlete-centred basis for RTS decision-making.

#### 4.1.4 Limited Use of Sport-Specific Tests

A consistent theme across both components of this thesis was the limited use of sport-specific assessments in RTS protocols. While strength and hop testing dominate current practice, these measures largely assess linear and closed-chain tasks performed in controlled settings. They provide valuable information on recovery of capacity and interlimb symmetry, but they fail to replicate the unpredictable, multidirectional, and cognitively demanding scenarios in which most ACL injuries occur (49, 56). This may have important implications for both the safety of RTS and the achievement of pre-injury performance levels.

Extensive evidence shows that non-contact ACL injuries most frequently occur during unanticipated cutting, pivoting, or deceleration manoeuvres, particularly in sports such as football, basketball, and rugby (3, 7, 9, 10, 50, 51, 128). Recent sport-specific analyses have further demonstrated that the predominant injury mechanisms vary markedly between sports; cutting and deceleration in football and basketball, landing in volleyball, and direct-contact situations in alpine skiing, for example (11). These contextual differences reinforce that RTS testing should be aligned to the biomechanical and perceptual demands of each sport rather than applying uniform benchmarks across all athletes.

Laboratory evidence reinforces this, showing that high-risk movements such as cutting and deceleration produce knee valgus moments and trunk deviations not captured by standard hop or strength tests (49, 183, 184). Athletes who demonstrate symmetry in hop distance or quadriceps strength may therefore still exhibit aberrant biomechanics in sport-specific contexts, leaving them vulnerable to reinjury once they resume competition. Consistent with these findings, Straub and Powers (185) reported that abnormal trunk-tibia and thigh angles during deceleration and side-step tasks on 2D video analysis predicted secondary ACL injury in female athletes. While the direct causal relationship between these identified asymmetries and subsequent reinjury remains incompletely established, warranting cautious interpretation, it underscores the value of movement quality assessments for detecting deficits missed by symmetry-based tests and highlights the need to include deceleration and cutting tasks in RTS batteries.

Field-based qualitative tools such as the Cutting Movement Assessment Score (CMAS) offer another pragmatic method for evaluating movement quality during CoD tasks. Unlike symmetry metrics, CMAS enables clinicians to identify high-risk kinematic patterns, such as excessive knee valgus or trunk deviation, using standard video recordings. CMAS has shown good reliability and clinical utility for detecting high-risk mechanics in both male and female athletes (50). While qualitative tools introduce subjectivity, when combined with objective timing or force measures they may offer a clinically feasible compromise between laboratory precision and field applicability. Incorporating CMAS alongside quantitative 2D video analysis of dynamic tasks could enhance RTS assessments by linking biomechanical risk profiling with feasible, on-field application.

Beyond safety, the absence of sport-specific assessments also constrains understanding of return to performance. King, Richter (186) showed that athletes post-ACLR can achieve symmetrical times in planned CoD tasks yet continue to load the surgical limb differently from the contralateral side. Furthermore, Wellsandt, Failla (47) demonstrated that hop tests often overestimate knee function compared to biomechanical measures of landing mechanics, suggesting that athletes cleared on hop criteria alone may not be performing at a level required for multidirectional sport. These findings question the ecological validity of relying solely on linear symmetry metrics for performance clearance.

It is unclear whether these asymmetries are associated with reinjury, but they are likely to impair agility, efficiency, and overall performance. Sport-specific assessments therefore have implications for performance progression. Dos'Santos, Thomas (54) highlighted that the ability to decelerate rapidly and re-accelerate is a critical determinant of performance in team sports, yet deceleration mechanics are rarely assessed in RTS protocols. Athletes may regain symmetrical hop distances yet remain unable to perform high-quality decelerations, limiting their effectiveness in competition.

The integration of reactive and ecologically valid testing has been advocated as a way to bridge the gap from RTS to return to performance. Reactive agility tasks, dual-task paradigms, and unanticipated CoD drills replicate the perceptual-cognitive demands of competition, where athletes must make split-second decisions in response to external stimuli (49). Studies have shown that adding cognitive load or external decision-making tasks exacerbates biomechanical asymmetries and exposes persistent deficits not evident under planned conditions (187, 188). Without testing under cognitive load, clinicians may underestimate residual risk and overstate an athlete's readiness to compete. However, standardisation of such reactive paradigms remains limited, and normative benchmarks are still emerging.

Metrics such as the reactive strength index (RSI), derived from drop jumps or repeated jump tests, provide insight into an athlete's ability to rapidly transition from eccentric to concentric contraction. This quality is critical for movements such as braking, pivoting, and re-accelerating, which can place substantial demands on the knee. In ACLR populations, reduced RSI has been reported even in athletes who otherwise achieve symmetrical hop distances, suggesting persistent deficits in neuromuscular efficiency and elastic energy utilisation (44, 105, 189). Beyond the ACL literature, RSI has been shown to correlate with agility performance in healthy athletes (190), and recent research has shown that athletes with higher RSI values demonstrate superior performance in planned and unplanned CoD tasks (191, 192). Brughelli, Cronin (193) highlight its role in eccentric control during high-speed braking, in part explaining these associations.

These findings reinforce reactive strength measures as a potentially valuable addition to RTS testing batteries. Tests such as a drop jump which provide RSI scores offer insight into neuromuscular efficiency and elastic energy use, which are closely tied to performance but are not captured by traditional hop metrics. By evaluating stretch-shortening cycle efficiency, RSI not only informs readiness for explosive lower-limb tasks but may also help predict an athlete's capacity to cope with the neuromechanical demands of multidirectional sport. However, these tests are rarely included in standardised RTS protocols. Expanding the use of RSI and linking it to functional outcomes such as CoD and deceleration performance could provide a more complete picture of sport readiness, bridging the gap between linear test performance and the complex demands of competition.

Taken together, limited use of sport-specific testing may represent an important limitation of current RTS decision-making. Standard batteries may confirm that an athlete is safe to train, but they offer little assurance that the athlete is prepared for the chaotic demands of competition, or is capable of regaining pre-injury performance levels. Accordingly, future RTS frameworks may benefit from integrating sport-specific, reactive, and movement-quality assessments within a structured, staged model rather than as adjuncts. Integrating such assessments may enhance ecological validity and support more informed, athlete-centred RTS decisions.

4.1.5 Emerging Models

The combined findings from this thesis support consideration of a more nuanced and integrated approach to RTS decision-making. Rigid adherence to LSI thresholds, particularly without consideration of psychological and contextual factors, may not accurately capture an athlete's readiness or risk profile. Rather than functioning as definitive clearance criteria, symmetry-based benchmarks may be better conceptualised as one component within a broader decision-making matrix. A multifactorial framework that includes strength, function, sport-specific ability, psychological readiness, and athlete-reported outcomes is likely to offer a more robust basis for decision-making. Future clinical models should also incorporate shared decision-making, recognising the athlete's perspective and goals as central to the return process.

An important contextual development in recent years has been the emergence of integrated care models such as Careway in Aotearoa NZ. Careway was established to streamline the management of ACL injuries through coordinated surgical, rehabilitation, and RTS care. One of its notable contributions has been the promotion of more consistent RTS testing across providers, including clear recommendations for objective strength and hop tests, psychological readiness measures, and defined timelines for progression. This model represents a national effort to reduce variability in RTS decision-making and improve outcomes through structured, evidence-informed pathways.

The clinical component of this thesis was conducted within a specialised physiotherapy setting operating under the Careway model, which likely contributed to the relatively high rate of psychological readiness screening (ACL-RSI) and the use of structured RTS batteries. However, despite this framework, variability still existed in how RTS thresholds were applied, and not all athletes completed the full test battery. This finding suggests that even within structured care models, clinical judgement, patient preference, logistical constraints, and individual recovery trajectories continue to shape RTS decisions. This highlights the tension between guideline-based care and the realities of individualised clinical practice.

Nevertheless, Careway and similar integrated care models mark a promising shift toward greater standardisation of ACL rehabilitation. However, their long-term impact on reinjury rates, performance outcomes, and equity of access remains to be fully evaluated. Such models may serve as a foundation for national benchmarking, longitudinal data collection, and refinement of RTS protocols over time, provided that ongoing evaluation accompanies implementation.

### 4.2 Strengths

One of the principal strengths of this thesis lies in its dual-study design, which combines a scoping review of the literature with a retrospective analysis of RTS outcomes following ACLR surgery in a clinical cohort. This complementary structure allowed for both a broad overview of best-practice RTS criteria and an in-depth evaluation of how these are applied in clinical practice. By integrating evidence synthesis with applied data, the thesis moves beyond descriptive mapping to critically examine the translational gap between research recommendations and clinical implementation.

The scoping review followed established methodological guidelines, including the Arksey and O'Malley framework and JBI recommendations, and was reported in accordance with PRISMA-ScR. Study selection and screening were undertaken using predefined eligibility criteria, and while the primary screening was conducted by a single reviewer, eligibility uncertainties were discussed with the supervisory team to enhance rigour and reduce selection bias. This structured approach enabled systematic mapping of RTS test components, thresholds, and decision-making strategies across 33 published studies. Importantly, the review did not merely catalogue test use, but identified patterns of variability and areas of inconsistency that have direct implications for comparability, benchmarking, and future guideline development. The review also contributed to the field by identifying underutilised domains, such as psychological readiness and sport-specific testing, which warrant greater consideration in future RTS frameworks.

The retrospective component of the thesis is another notable strength. With a sample of 166 participants assessed at a specialised physiotherapy clinic in Aotearoa NZ, the study provided a broad, real-world view of RTS performance outcomes across multiple domains. The inclusion of objective strength, jump, and psychological measures within a structured

RTS battery enhances ecological validity and reflects contemporary clinical practice rather than controlled laboratory conditions.

This clinical dataset allowed for analysis of pass rates, limb symmetry achievement, and associations with demographic and surgical variables. Importantly, the secondary analysis of higher performance thresholds added depth to the findings and contributed to the emerging discourse on whether ≥90% LSI is sufficiently stringent for RTS clearance.

Collectively, the integration of evidence synthesis with real-world cohort data strengthens the external relevance of the findings and supports more contextually grounded interpretation of RTS decision-making processes.

### 4.3 Limitations

Despite its strengths, this thesis has several limitations that should be acknowledged. Firstly, the scoping review, by design, prioritises breadth over depth and does not include formal appraisal of study quality. As such, while the review identifies key themes and patterns, it does not differentiate findings based on study quality or risk of bias. This limits the ability to draw definitive conclusions regarding the superiority of specific RTS tests or thresholds. Additionally, it was limited to English-language peer-reviewed studies and excluded grey literature, which may have led to the omission of relevant studies.

Furthermore, although structured eligibility criteria were applied, screening was not independently duplicated at all stages. While supervisory consultation occurred where required, the absence of full dual-reviewer screening may introduce potential selection bias, which should be considered when interpreting the comprehensiveness of included studies.

The retrospective nature of the clinical analysis also presents several limitations. As data were collected during routine clinical care, there were instances of missing or incomplete information, particularly in cases where participants did not complete the full RTS battery. This reflects real-world practice but may have introduced sampling bias, particularly if higher-functioning athletes were more likely to complete testing. Consequently, pass rates may either overestimate or underestimate true functional recovery within the broader ACLR population.

Additionally, the sample was drawn from a single specialised physiotherapy practice operating within the Careway integrated care model. While this enhances internal consistency, it may limit generalisability to other regions, healthcare systems, or settings without structured RTS frameworks.

Another limitation relates to the RTS outcome variable. RTS outcome was recorded via self-report and categorised into five levels. While this provided useful insight into the spectrum of return outcomes, it is subject to recall bias and may not fully reflect performance level, competition exposure, or sport-specific demands. Moreover, RTS decisions are influenced by multifactorial contextual factors, including team selection, contract status, psychosocial readiness, and personal choice, that were not controlled for in this analysis. These external influences may partially explain discrepancies observed between physical test performance and actual RTS outcomes.

Finally, although effect sizes were calculated to support interpretation of statistically significant findings, the retrospective design and moderate subgroup sizes reduce statistical power for certain comparisons, particularly where multiple categories were examined. As such, some non-significant findings should be interpreted cautiously, as absence of statistical significance does not necessarily equate to absence of clinically meaningful difference.

### 4.4 Clinical Implications & Future Directions

The findings of this thesis highlight both the progress and persistent challenges in RTS decision-making after ACLR surgery. Although strength and hop testing remain central to most RTS protocols, this work confirmed that variability in test selection, pass thresholds, and timing continues to undermine comparability across studies and clinical practice. Such heterogeneity complicates benchmarking, limits meaningful cross-study comparison, and may contribute to inconsistent clinical decision-making across settings. Moreover, the clinical analysis demonstrated that despite extended rehabilitation timeframes, relatively few athletes achieved commonly recommended benchmarks, and even fewer reached the more stringent thresholds thought to be protective against reinjury. These findings suggest that current RTS frameworks, while conceptually robust, may not consistently translate into attainable or functionally meaningful outcomes for all athletes.

At the same time, psychological readiness emerged as a consistent determinant of RTS outcomes, often exerting stronger influence than physical symmetry alone. This reinforces the growing recognition that RTS is not solely a biomechanical milestone, but a multidimensional process shaped by confidence, fear of reinjury, and contextual pressures. Together, these findings underscore the limitations of a “one-size-fits-all” approach based on fixed thresholds and highlight the need for RTS models that are more standardised yet simultaneously more individualised. Rather than abandoning objective criteria, future models may need to reposition them within a broader framework that integrates physical capacity, movement quality, psychological readiness, and sport-specific demands.

Future approaches should therefore address both the content and timing of testing, integrate psychological and sport-specific measures, and consider demographic, surgical, and contextual factors that shape recovery trajectories. Structured interim testing, longitudinal monitoring beyond initial return, and shared decision-making processes may offer more nuanced approaches than single time-point clearance decisions.

Building on these insights, the following sections outline key clinical and research priorities. These include: (1) achieving greater standardisation of RTS test batteries, thresholds, and timing; (2) moving toward stratified, individualised clearance frameworks; (3) integrating sport-specific assessments; (4) enhancing the role of psychological readiness in RTS decision-making; (5) embedding longitudinal monitoring beyond the point of initial return; (6) optimising prehabilitation and rehabilitation strategies; and (7) ensuring inclusivity by extending research to more unrepresented populations. Collectively, these directions provide a roadmap for advancing RTS testing toward more robust, contextually relevant, and athlete-centred models.

Collectively, these directions suggest that future RTS models should aim not only to reduce reinjury risk, but also to support sustainable return to performance within the complex ecological demands of competitive sport.

#### 4.4.1 Standardisation of RTS Tests, Pass Thresholds and Timing

One of the most pressing areas for future research is the establishment of consensus around RTS test batteries, pass thresholds, and timing of assessment. The current landscape remains fragmented, with substantial heterogeneity in test selection (strength, hop, agility, psychological measures), the order in which tests are performed, and the thresholds applied to determine readiness. This inconsistency limits comparability across studies and reduces the clinical utility of RTS testing in practice.

For example, a survey in Aotearoa NZ demonstrates that physiotherapists most frequently rely on quadriceps strength, hop testing, and psychological readiness, with time from surgery also commonly considered for RTS decision making (35). However, variability in implementation is high; some clinicians use hop testing primarily as a proxy for knee strength, while others incorporate it within broader movement assessments. This heterogeneity contrasts with recent guideline recommendations that stress the need for rigorous, multidomain assessment, rather than reliance on a single measure such as hop distance symmetry (194).

In addition to inconsistency in test selection, the timing of RTS assessments remains unclear. Many athletes are tested only once, typically at the end of supervised rehabilitation or around arbitrary timepoints (e.g., 6 or 9 months post-surgery), rather than as part of an ongoing decision-making continuum (4). Emerging evidence, however, suggests that interim testing can be valuable. Bodkin, Bruce (158) reported that structured interim assessments improved both strength symmetry and patient-reported outcomes, emphasising their role in guiding progression. The Aspetar model, described by Kotsifaki, Korakakis (20), provides a benchmark in this regard, advocating for progressive reassessment every six weeks with criteria-based advancement through rehabilitation stages.

More recently, Kotsifaki, King (159) extended this work in a large cohort of male footballers, showing that athletes who completed structured rehabilitation and met objective discharge criteria could safely return to pivoting sports before nine months post-surgery without increased reinjury risk. These findings highlight the importance of both rehabilitation quality and objective clearance criteria, rather than time alone, as determinants of safe RTS.

Future frameworks should therefore address both content and timing; not only defining which tests and thresholds to include but also specifying how often and at what stages they should be conducted across the RTS continuum. Reaching agreement will likely require international consensus panels to develop a universally accepted test battery with evidence-based thresholds that balance safety, feasibility, and ecological validity.

4.4.2 Integration of Sport-Specific Assessments

As discussed earlier, while jump, hop, and strength tests form the backbone of current RTS protocols, they may not adequately reflect the dynamic, multidirectional, and unpredictable demands of sport. Most ACL injuries occur during unanticipated cutting, pivoting, or deceleration movements (54, 120, 128), yet these are seldom represented in RTS test batteries. This gap risks returning athletes to competition without sufficient exposure to the movement patterns that most commonly cause reinjury. Recent large-scale situational analysis confirms that ACL injury mechanisms vary considerably between sports, with cutting and deceleration-based injuries dominating in football and basketball, while landing and direct-contact mechanisms being more prevalent in sports such as volleyball and alpine skiing (11). These findings highlight the need for RTS assessments to reflect sport-specific demands rather than relying solely on universal hop or strength benchmarks. As Welling and Frik (129) note, without sport-specific or on-field assessments, clinicians have “incomplete information about a patient’s physical capacity” (p. 6).

Traditional planned CoD tests, such as the T-test, Pro-Agility, or Modified Illinois CoD Test (MICODT), offer valuable insights into linear speed and controlled directional change but fail to capture the perceptual-cognitive demands of sport, where decisions are made in response to unpredictable cues (53). In contrast, unplanned and reactive CoD assessments, such as the unplanned 90° CoD test or the Reactive Agility Test (RAT), integrate external stimuli (e.g., light or assessor cues) that more accurately replicate real-game scenarios (93, 100, 130). These tasks elicit substantially higher knee joint loads, sometimes twice those of pre-planned tasks (49, 129), highlighting their relevance for evaluating neuromechanical readiness. Nonetheless, reactive agility and CoD tasks remain underutilised in RTS protocols. Many studies continue to rely on interlimb timing metrics, which may obscure underlying biomechanical asymmetries (46, 130).

Recent evidence has further questioned the validity of symmetry-based criteria for RTS, showing that even athletes achieving high LSI were not necessarily protected from reinjury. Hamrin Senorski, Piussi (179) demonstrated LSI cut-offs could not differentiate between athletes who safely returned to sport and those who reinjured, underscoring the need to complement strength and hop symmetry with dynamic, sport-specific assessments.

While 3D motion capture remains the gold standard for detecting these movement deficits, its cost and complexity limit its clinical applicability. Field-based alternatives, such as the CMAS, a qualitative tool for identifying high-risk kinematic patterns during cutting, offer a pragmatic substitute (50). When combined with video-based analysis and interlimb timing data, CMAS and similar assessments can provide a more holistic evaluation of movement quality. Building on this, Straub and Powers (185) demonstrated that simple 2D video-based measures of trunk-tibia, knee valgus, thigh, and pelvic tilt angles during deceleration and side-step cutting tasks accurately predicted secondary ACL injury in female athletes. Incorporating such 2D analyses into RTS testing provides a feasible bridge between laboratory biomechanics and clinical practice, allowing clinicians to quantify high-risk kinematics within standard field-based assessments.

In parallel, emerging wearable sensor systems and portable force-plate technologies offer additional potential for monitoring of neuromechanical readiness. Metrics such as braking impulse, centre-of-mass velocity at initial contact, and asymmetrical load distribution can complement 2D video analysis by quantifying load-management strategies not visible through kinematic assessment alone (50, 122, 129). These technologies collectively enhance clinicians' ability to detect compensations that might otherwise go unnoticed during standard strength or hop testing.

Beyond agility and CoD, deceleration ability is increasingly recognised as a critical component of RTS readiness and long-term joint protection. High-intensity braking generates eccentric loads of up to three times body weight within 50 milliseconds of ground contact, demanding rapid force attenuation, coordination, and control (195). After ACLR, persistent quadriceps inhibition and altered braking mechanics can lead to asymmetrical load distribution and greater reliance on passive restraints, elevating reinjury risk (196). As mentioned, Straub and Powers (185) identified aberrant trunk-tibia and thigh angles during a deceleration task as significant predictors of secondary ACL injury in female athletes. Their findings demonstrate that movement-quality analysis during braking provides clinically meaningful insight into neuromechanical readiness and reinjury risk, validating the inclusion of deceleration assessment as both a diagnostic and training tool in late-stage rehabilitation.

Sheth and Elis (197) define deceleration as the capacity to reduce whole-body momentum while skilfully absorbing and redirecting force; a trainable skill that should be developed progressively rather than introduced only in late-stage rehabilitation. Structured exposure beginning with controlled eccentric and positional drills, advancing toward multi-planar, high-velocity braking and reactive tasks, enhances proprioceptive control and safe penultimate-foot strategies that reduce stress during rapid CoD. Incorporating systematic frameworks for progression enables clinicians to translate strength gains into functional, high-speed control, bridging the gap between traditional rehabilitation and the mechanical realities of sport.

Sprinting capacity also warrants deliberate inclusion in RTS assessment and training. Sprinting exposes the knee to high eccentric demands during late swing and impact loading at ground contact, movements integral to both injury occurrence and performance recovery. Applying velocity-based training (VBT) principles enables clinicians to reintroduce sprinting progressively, monitor mechanical load, and track neuromuscular readiness (198). Integrating sprint-based metrics with CoD and deceleration testing better represents the complete spectrum of sport-specific demands.

Taken together, combining reactive agility, deceleration, and sprint assessments offers a more ecologically valid, sport-specific framework for RTS decision-making. In the clinical cohort investigated in this thesis, CoD or reactive agility measures were not included, limiting evaluation of these higher-level functional components. Future research should focus on validating integrated, sport and environment specific assessments that reflect the physical, cognitive, and mechanical complexity of sport. By moving beyond isolated strength, jump and hop symmetry, clinicians may better identify athletes who may be technically symmetrical but functionally unprepared, ultimately reducing reinjury risk and improving long-term RTS outcomes.

#### 4.4.3 Enhanced Use of Psychological Readiness Measures

Psychological readiness remains underutilised in RTS decision-making despite strong evidence linking it to successful outcomes. Low ACL-RSI scores consistently predict unsuccessful return (68), and fear of re-injury is one of the most common reasons athletes withdraw from sport (132, 135, 180). Findings from this thesis similarly highlighted the importance of psychological readiness, with reduced readiness strongly associated with lower rates of RTS success in the clinical cohort assessed.

Despite this evidence, psychological outcomes are inconsistently measured in clinical practice, and meaningful cut-offs for RTS clearance remain poorly defined. Future research should focus on identifying which psychological tools and domains are most predictive of long-term outcomes, and on establishing clinically actionable thresholds that can guide RTS clearance. Furthermore, longitudinal approaches that track changes in confidence, fear, and motivation may provide insight into how psychological readiness interacts with physical recovery trajectories.

Longitudinal and mixed-methods approaches are particularly warranted. Tracking psychological readiness over time may clarify how changes in confidence, fear, and motivation interact with physical recovery trajectories and reinjury risk. Incorporating qualitative inquiry alongside quantitative measures would also provide richer insight into athletes' lived experiences during rehabilitation, highlighting cultural, social, and contextual factors that influence recovery beliefs and motivation (199, 200). Such approaches would allow clinicians to tailor rehabilitation strategies not only to restore physical performance but also to actively cultivate the psychological resilience, self-efficacy, and confidence essential to sustained participation in sport.

#### 4.4.4 Individualisation

Beyond standardisation, there is a parallel need to better individualise RTS decision-making. Current "one-size-fits-all" thresholds (e.g., ≥90% LSI for strength and hop tests) risk oversimplifying recovery and failing to account for athlete-specific demands or risk profiles (164). Evidence indicates that the risk of reinjury is not uniform across all athletes. Research has highlighted that reinjury rates are substantially higher in pivoting and cutting sports such as football, basketball, netball and rugby compared with endurance or non-pivoting sport (35). This suggests that RTS thresholds should be aligned to the specific biomechanical and contextual demands of different sports.

To address this gap, this thesis proposes a conceptual framework that stratifies sports into risk categories and aligns them with corresponding symmetry thresholds. Importantly, this framework is theoretical and intended to stimulate discussion and future validation rather than serve as a definitive clinical guideline. This model assumes that strength and functional symmetry targets should scale with the mechanical demands of the sport. Table 8 presents proposed knee-strength LSI thresholds for different sport categories, demonstrating how RTS criteria could potentially be adapted across the risk spectrum.

*Table 8: Proposed Strength LSI Thresholds for RTS Decision-Making Based on Sport Risk Level*

| **Sport Risk Level** | **Examples** | **LSI Threshold for Return to Participation (RTPart)** | **LSI Threshold for RTS** |
|---|---|---|---|
| **Level I: frequent pivoting** | Football, rugby, netball, basketball | ≥85% | ≥95% |
| **Level II: occasional pivoting** | Tennis, alpine skiing, snowboarding, gymnastics | ≥80% | ≥90% |
| **Level III: minimal pivoting** | Running, cross-country skiing, weightlifting | ≥70% | ≥80% |

The framework, outlined in Figure 14, builds on earlier classifications of sport risk (201) and principles from prognostic research (202) but extends these into a decision-making framework for RTS clearance. While grounded in existing literature, prospective validation is required to determine whether stratified thresholds meaningfully influence reinjury rates or performance outcomes.

*Figure 14: Proposed RTS Test and Decision-Making Framework*

Beyond sport type, individual risk modifiers further refine clearance thresholds. Factors such as sex, mechanism of injury, family history, anatomical morphology, and prior ACL injury can amplify reinjury risk (203). These intrinsic elements are summarised in Table 9, which highlights variables clinicians may consider when tailoring decision criteria.

*Table 9: Risk Factors for Second ACL Injury*

| **Criterion** | |
|---|---|
| **Gender** | Female |
| **Anterior Knee Laxity** | >3 mm translation |
| **Mechanism of Injury** | Non-contact |
| **Family History** | Immediate family history of ACL tear |
| **Level of Sport** | Returning to level 1 sport (elite/pivoting) |
| **Anatomy** | Steeper posterior-inferior tibial plateau slope compared to uninjured athletes, determined by surgeon |
| | Decreased notch width index (NWI) compared to uninjured athletes, determined by surgeon |
| **Past Medical History** | Contralateral or ipsilateral ACL tear |

Interim assessments are introduced from the early postoperative period, beginning with range of motion and symmetry goals at six and 12 weeks, progressing to strength, functional jump assessments, and psychological readiness testing at regular 6-week intervals. As athletes progress, clearance decisions for return to participation through to return to competition (RTS) are stratified according to sport risk level and individual intrinsic risk factors, as shown in Table 10.

Athletes returning to minimal-pivoting sports (level III) may reasonably achieve RTS clearance once core strength, function, and psychological readiness criteria are achieved. Athletes in high-risk pivoting sports (level I) may require stricter strength thresholds, additional agility and CoD assessments and completion of a sport-specific rehabilitation programme that includes progressive acceleration, deceleration, pivot, cut and sidestep tasks, including dual-task conditions, individualised to position-related sporting demands. Where multiple intrinsic risk factors exist, such as female sex, non-contact injury mechanism, family history of ACL rupture, or steep tibial slope, higher performance benchmarks (e.g., ≥95% LSI, elevated psychological readiness scores) and delayed clearance may be warranted (6, 171, 203, 204).

For example, a female athlete returning to elite pivoting sport with a family history of ACL rupture and anatomical risk factors could require not only ≥95% strength symmetry but also successful completion of reactive agility and CoD tasks, a sport specific rehabilitation programme and evidence of strong psychological confidence before clearance. Conversely, an endurance athlete in a low-risk sport may be appropriately cleared with lower thresholds once functional and psychological readiness are demonstrated.

By moving beyond rigid universal cut-offs, this staged and stratified framework aims to encourage more nuanced, contextually relevant RTS decision-making. However, the framework should be interpreted as a hypothesis-generating model rather than an established standard. Future research should test and refine this model through prospective validation, examining how interim testing, stratified thresholds, and individual risk profiling influence RTS timing, reinjury rates, and long-term knee health. This staged approach is consistent with emerging international rehabilitation models such as the Aspetar Clinical Practice Guideline on ACL Rehabilitation (Kotsifaki et al., 2025), which emphasises progressive, criteria-based progression through rehabilitation phases and supports context-specific RTS frameworks that balance safety with ecological validity (20). Alignment with evolving guidelines may strengthen the translational applicability of the proposed framework while maintaining appropriate clinical caution.

*Table 10: Individualised Return to Participation (RTPart) and RTS Test Framework*

| RTS Domain | Tests | $RTP_{ART}$ | | RTS | |
|---|---|---|---|---|---|
| **Hop and Jump** | 1. Single Hop for Distance<br>2. Single Leg Vertical Jump<br>3. Countermovement Jump<br>4. Single Leg Drop Jump [RSI] *(only in advanced RTS test)* | **Level I** | ≥85% LSI<br>2D analysis = no high-risk patterns on hop and drop jump | **Level I** | ≥95% LSI<br>2D analysis = no high-risk patterns on hop and drop jump |
| | | **Level II** | ≥80% LSI | **Level II** | ≥90% LSI |
| | | **Level III** | ≥70% LSI | **Level III** | ≥80% LSI |
| **Strength** | 1. Knee Extension Strength (IKD or PFD)<br>2. Knee Flexion Strength (IKD or PFD) | **Level I** | ≥85% LSI and EPIC<br>*H:Q = 55%* | **Level I** | ≥90% LSI and EPIC<br>*H:Q = 60%* |
| | | **Level II** | ≥80% LSI and EPIC<br>*H:Q = 50%* | **Level II** | ≥90% LSI and EPIC<br>*H:Q = 55%* |
| | | **Level III** | ≥70% LSI and EPIC<br>*H:Q = 45%* | **Level III** | ≥80% LSI and EPIC<br>*H:Q = 50%* |
| | 3. Unilateral Leg Press 1RM | **Level I** | 200%BW | **Level I** | 225%BW |
| | | **Level II** | 150%BW | **Level II** | 200%BW |

| | | | | | |
|---|---|---|---|---|---|
| | | **Level III** | 125%BW | **Level III** | 150%BW |
| **Sport Specific CoD and Agility** *(only in advanced RTS test)* | 1. Reactive T-test<br>2. Deceleration<br>3. Side-step | **Level I** | CMAS = ≤4<br>2D analysis = no high-risk patterns | **Level I** | CMAS = ≤3<br>2D analysis = no high-risk patterns |
| | | **Level II** | CMAS = ≤5<br>2D analysis = ≤2 high-risk patterns | **Level II** | CMAS = ≤3<br>2D analysis = ≤2 high-risk patterns |
| | 4. Completion of a sport-specific rehabilitation programme (e.g., on field or court) | | | | |
| **Psychological Readiness** | 1. ACL-RSI | **Level I** | ≥60 | **Level I** | ≥75 |
| | | **Level II** | ≥60 | **Level II** | ≥75 |
| | | **Level III** | ≥50 | **Level III** | ≥60 |
| Note: 1RM = One repetition maximum, CMAS = Cutting movement assessment score, EPIC = Estimated pre-injury capacity, H:Q = Hamstring-to-quad ratio, IKD = Isokinetic dynamometry, LSI = Limb symmetry index, PFD = Portable fixed dynamometry, %BW = Percentage of body weight, $RTP_{ART}$ = Return to participation, RTS = Return to sport, RSI = Reactive strength index | | | | | |

#### 4.4.5 Longitudinal Tracking of RTS Outcomes and Re-Injury Risk

Much of the existing evidence base for RTS testing remains retrospective or cross-sectional, limiting its ability to capture the dynamic and evolving nature of recovery. There is a pressing need for large-scale, prospective longitudinal studies that follow athletes from early rehabilitation through RTS and into the long term. Such research should capture not only short-term outcomes such as time to RTS and initial reinjury incidence, but also performance levels, revision surgery, persistent functional deficits, and patient-reported outcomes over years.

Mapping outcomes across the RTS continuum, return to participation, competition, and performance, would enable researchers to determine which test batteries and thresholds best predict safe and sustained return (205). These longitudinal approaches are particularly important for identifying delayed recovery trajectories, monitoring reinjury risk beyond the initial return, and evaluating the effectiveness of different rehabilitation models.

Such work is critical for shifting RTS testing from isolated, time-point assessments to a more holistic, dynamic model of recovery. Ultimately, longitudinal evidence could underpin the development of adaptive RTS frameworks that are responsive to individual progress, integrate physical and psychological factors, and support athletes in achieving not just RTS, but sustainable, high-level participation.

#### 4.4.6 Impact of Prehabilitation and Rehabilitation Strategies

This thesis demonstrated that prehabilitation was associated with improved knee flexion strength symmetry, although gains in quadriceps strength were not significant. While this association should be interpreted cautiously given the retrospective design, other research indicates that greater preoperative quadriceps strength is a key predictor of superior postoperative function and long-term outcomes (153, 206). The absence of significant quadriceps gains in this cohort may reflect variability in programme content, intensity, or adherence, highlighting a potential gap in current prehabilitation practice. These findings suggest that future programmes may benefit from placing greater emphasis on targeted quadriceps strengthening alongside broader lower-limb conditioning.

The importance of quadriceps-focused prehabilitation is reinforced by findings from the systematic review conducted by Potts, Reid (163). Their review of preoperative exercise interventions found that four to 16 weeks of structured prehabilitation can significantly improve quadriceps strength prior to ACLR surgery. However, the evidence for sustained postoperative benefits was less consistent, reflecting considerable variability in programme content, dosage, and quality. The authors concluded that while prehabilitation is effective at enhancing preoperative strength, further high-quality randomised controlled trials are needed to determine the optimal protocols that lead to long-term functional improvements. This aligns with the suggestion that future research should not only refine exercise prescription but also evaluate the timing and intensity of interventions required to translate preoperative gains into durable outcomes

Beyond quadriceps strength, prehabilitation provides an opportunity to address neuromuscular control, movement quality, and psychological readiness. Interim assessments during the preoperative period may be particularly valuable. They allow clinicians to identify deficits, adjust rehabilitation strategies accordingly, and set more personalised performance targets (158). The use of estimated pre-injury capacity (EPIC) thresholds represents one such approach, anchoring rehabilitation goals to pre-injury or pre-operative measures of the uninvolved limb rather than relying solely on symmetry indices at a single time point (47). By benchmarking against the athlete’s own pre-injury capacity, EPIC thresholds may offer a more individualised reference point for recovery, although prospective validation is required to determine their predictive value for RTS outcomes (1).

Post-operative rehabilitation strategies may also require refinement. Current evidence supports the inclusion of progressive loading, plyometric training, and sport-specific rehabilitation in the later stages of recovery (114), yet substantial variability remains in how these elements are sequenced and progressed across clinical settings. This heterogeneity mirrors the variability observed in RTS testing and may partly explain persistent asymmetries despite extended rehabilitation durations. A more integrated model linking structured prehabilitation, interim testing, EPIC-informed benchmarks, and progressive postoperative rehabilitation may enhance coherence across the rehabilitation continuum, potentially improving both performance restoration and reinjury mitigation.

Emerging research further highlights the value of hormone-informed or menstrual cycle-specific assessments into rehabilitation monitoring. While O'Loughlin, Reid (207) et al. found no significant strength or function advantage of menstrual cycle-phased rehabilitation compared with usual care, qualitative follow-up research revealed meaningful benefits in motivation, engagement, and perceived recovery among female participants (208). Participants described increased body awareness, improved confidence, and strong programme acceptability. These findings suggest that even where objective performance outcomes are equivalent, individualised and hormone-informed approaches may influence adherence and athlete experience, factors that are highly relevant to long-term rehabilitation success.

In practice, scheduling key strength or power assessments during the follicular phase may optimise test reliability and minimise hormonal variability, given oestrogen's anabolic and progesterone's catabolic effects (209, 210). Furthermore, tests that emphasise neuromuscular control, such as knee valgus moments and landing kinematics may be particularly informative for female athletes, who are more prone to frontal-plane instability (173). However, females remain underrepresented in ACLR research, and current rehabilitation and RTS criteria largely derive from male cohorts. Greater inclusion of women and consideration of physiological sex differences may therefore strengthen the ecological validity of future rehabilitation models.

Future research should therefore prioritise investigating how targeted quadriceps-focused prehabilitation, combined with structured interim testing and personalised benchmarks, influences rehabilitation progression, reinjury rates, and athlete confidence. Importantly, such studies should evaluate interactions between preoperative strategies and postoperative programming while incorporating sex-specific and hormone-informed considerations. Longitudinal designs will be particularly important in determining whether early strength gains translate into sustained functional resilience and reduced reinjury risk.

#### 4.4.7 Inclusion of Diverse Populations and Sporting Contexts

Historically, RTS research has been dominated by studies involving young, male, European or North American elite athletes, limiting the generalisability of findings to the wider ACLR population. There is a pressing need for greater inclusion of female athletes, recreational participants, older adults, and individuals from underrepresented cultural groups to enhance external validity and promote equity in rehabilitation outcomes.

In Aotearoa NZ, Māori and Pasifika athletes experience disproportionately high rates of cruciate ligament injuries yet remain underrepresented in ACL research (19, 136). Addressing this imbalance requires not only more inclusive participant recruitment but also research designs that consider Māori and Pacific research principles, ensuring that data collection, interpretation, and dissemination are culturally grounded. Future studies should explore how social determinants, such as access to specialised rehabilitation, socioeconomic factors, and culturally safe clinical environments, influence recovery and RTS trajectories (177). Developing partnerships with Māori and Pasifika clinicians, communities, and athletes is essential to co-create rehabilitation models that reflect diverse values, sporting identities, and definitions of success.

Cultural context, communication, and trust between clinician and athlete also influence motivation and adherence, both of which are crucial for achieving optimal RTS outcomes. For many Māori and Pasifika athletes, healing and recovery are experienced not solely as physical processes but as a holistic journey. Future research should embed *Kaupapa* Māori frameworks, which emphasise *tino rangatiratanga* (self-determination), collective benefit, and research by and for Māori communities (177, 211). These approaches position Māori worldviews and values, such as *whanaungatanga* (relationships), *manaakitanga* (care and respect), and *kotahitanga* (collective unity), as central to both research design and clinical application. These frameworks emphasise partnership, participation, and protection in accordance with The Treaty of Waitangi (212).

Importantly, integrating culturally grounded methodologies does not replace evidence-based rehabilitation but rather strengthens it by ensuring contextual relevance and equity. Rehabilitation frameworks that incorporate indigenous models of health recognise the interdependence of physical, mental, social, and spiritual wellbeing, aligning more closely with holistic understandings of recovery.

Greater inclusion of diverse sporting contexts is also warranted. Much of the existing literature focuses on elite pivoting sports, yet many ACLR patients participate in recreational sport. Expanding research to encompass varied participation levels may clarify whether RTS thresholds and testing models should be adapted according to exposure intensity and performance expectations.

In summary, advancing RTS research requires not only refinement of biomechanical and psychological models but also broader representativeness and cultural responsiveness. Equity-focused and partnership-driven approaches may enhance both the scientific validity and social impact of ACLR research. Culturally anchored methodologies have the potential to enrich RTS frameworks, ensuring they honour the identities, values, and aspirations of Māori, Pasifika, and other underrepresented athletes within Aotearoa NZ.

**Conclusion**

This thesis explored RTS testing following ACLR surgery through a scoping review of the literature and analysis of clinical data from a specialised rehabilitation setting in Aotearoa NZ. Together, these studies addressed key questions regarding current best practice, performance outcomes, timing of clearance, and the factors influencing RTS success. Across the literature, RTS testing remains inconsistent and predominantly focused on physical measures of quadriceps strength and hop performance. Few protocols incorporate psychological or sport-specific assessments, despite growing evidence that these domains are critical to safe and sustained RTS.

In the clinical cohort investigated in this thesis, overall RTS test pass rates were modest. The average time to RTS assessment was approximately 12 months post-surgery. No significant associations were found between RTS outcomes and age, sex, ethnicity, graft type, or sport type, suggesting that readiness is shaped more by individual recovery trajectories than by demographic characteristics. Only a very small proportion of athletes achieved high-test performance thresholds (≥95% LSI), and there was no association between achieving this threshold and RTS outcomes. Psychological readiness was more strongly associated with RTS success than individual physical variables within this cohort.

Collectively, these findings highlight the limitations of rigid, “one-size-fits-all” criteria and support the adoption of integrated, context-specific RTS frameworks. Combining progressive physical testing with psychological assessment, risk stratification by sport type, and culturally responsive rehabilitation may improve both the safety and equity of RTS decisions after ACLR. Ultimately, RTS should be viewed as a dynamic process that balances performance goals, athlete confidence, and long-term knee health.

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## Appendices

## Appendix A. Ethics Application Approval Letter

**Auckland University of Technology Ethics Committee (AUTEC)**

15 August 2024

Duncan Reid
Faculty of Health and Environmental Sciences

Dear Duncan

Re Ethics Application: **24/203 A retrospective descriptive analysis of return to sport (RTS) testing after anterior cruciate ligament reconstruction (ACLR) surgery in Aotearoa New Zealand (Aotearoa NZ)**

Thank you for your responses to AUTEC's conditions.

Your ethics application has been approved for three years until 15 August 2027.

**Standard Conditions of Approval**

1. The research is to be undertaken in accordance with the Auckland University of Technology Code of Conduct for Research and as approved by AUTEC.
2. All public facing documents must have the AUTEC approval number and be of a high standard of spelling and grammar. Dates on the Information Sheet(s) and Consent Form(s) must be consistent.
3. Any amendments to the project must be approved by AUTEC prior to being implemented.
4. A progress report is due annually on the anniversary of the approval date.
5. A final report is due at the expiration of the approval period, or, upon completion of project.
6. Any serious or adverse events must be reported to AUTEC, this includes unforeseen issues that might affect continued ethical acceptability of the project.
7. AUTEC grants ethical approval only. You are responsible for obtaining management permission for access from any institution or organisation at which your research is being conducted and you need to meet all ethical, legal, public health, and locality obligations or requirements for the jurisdictions in which the research is being undertaken.

The application number and title need to be referenced on all correspondence related to this project.

All forms are available online http://www.aut.ac.nz/research/researchethics

For any enquiries, please contact ethics@aut.ac.nz
(This is a computer-generated letter for which no signature is required)

The AUTEC Secretariat
**Auckland University of Technology Ethics Committee**

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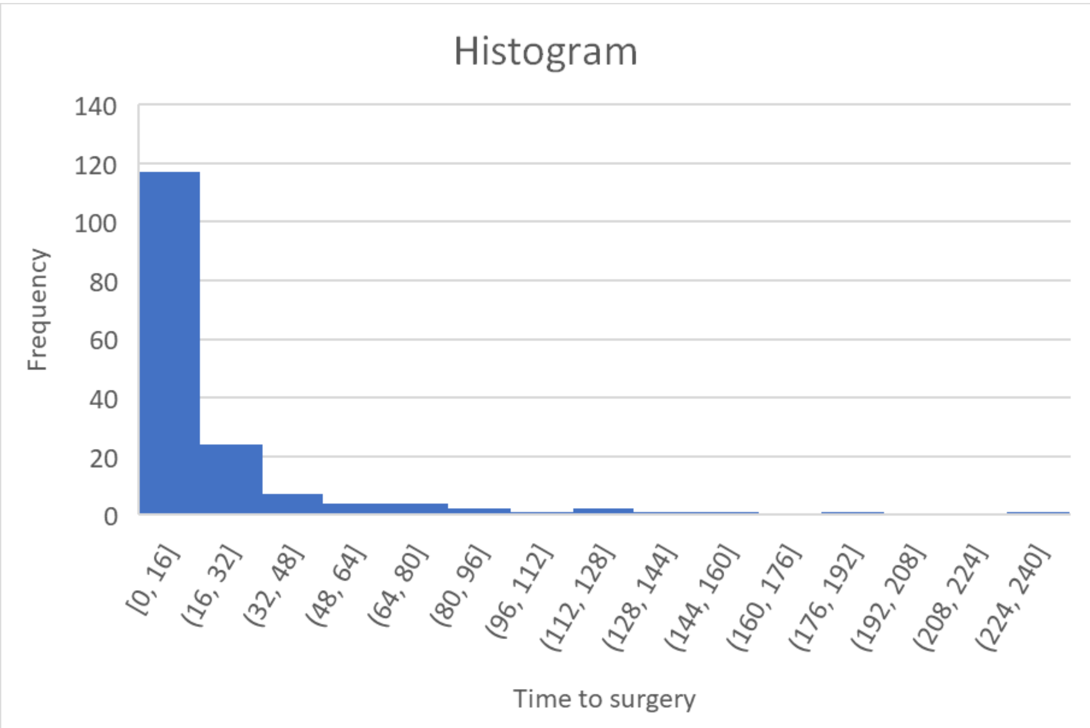
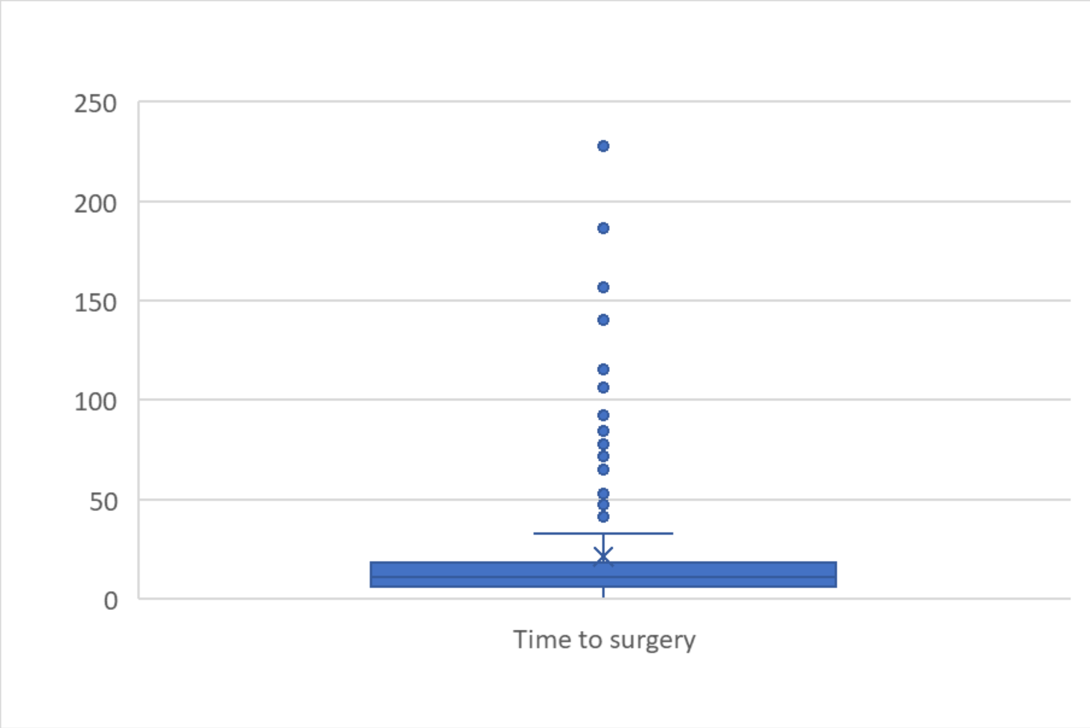
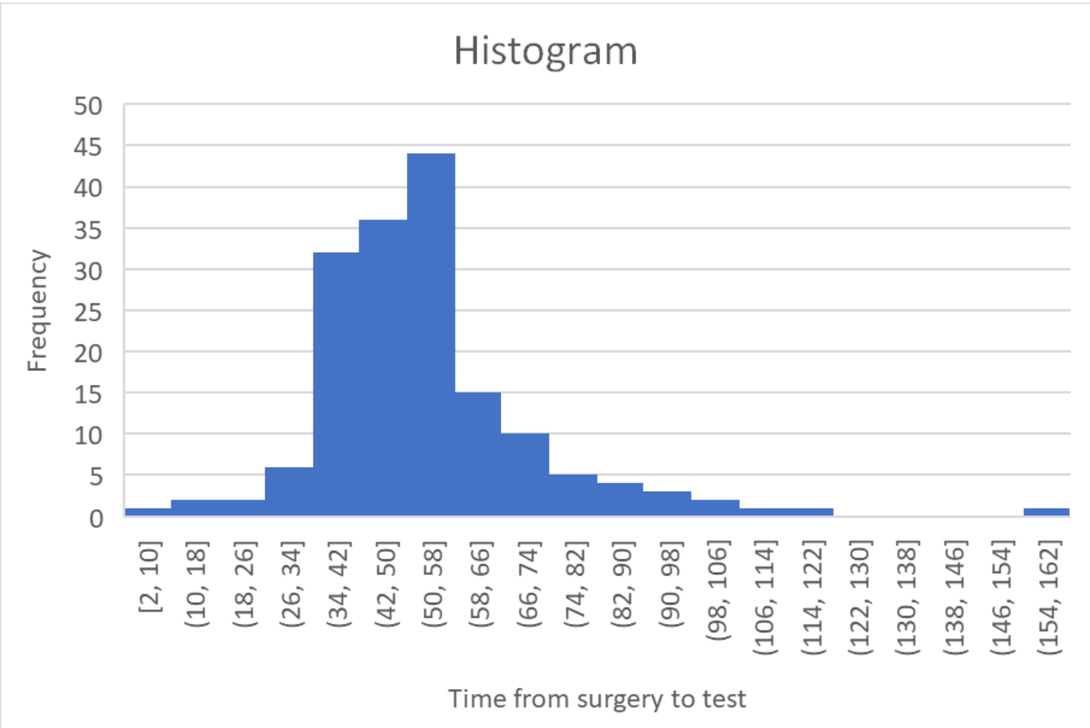
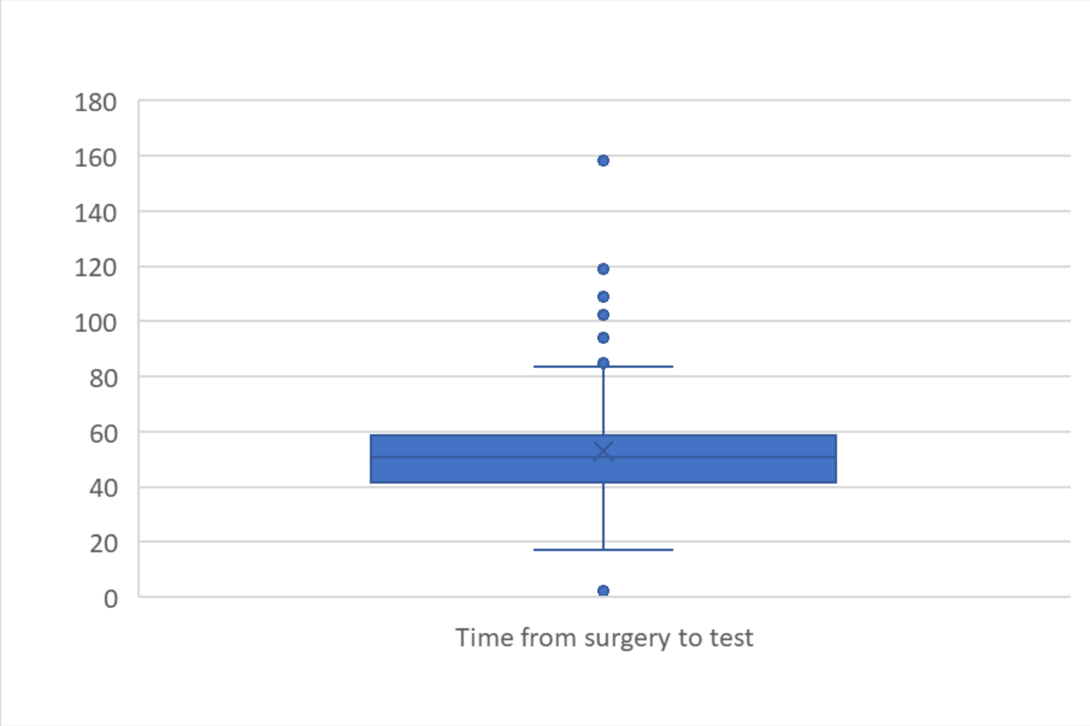
**Appendix B. Time to Surgery and Time from Surgery to Test Descriptive Statistics, Test Percentile Values, Histograms and Boxplot Graphs**

| Measure | Mean | Median | SD | Min | Max | IQR | Skewness | Kurtosis |
|---|---|---|---|---|---|---|---|---|
| **Time to surgery** | 21.0688 | 11.1 | 32.85456 | 0.0 | 228.0 | 11.85 | 3.647 | 15.511 |
| **Time from surgery to test** | 52.9388 | 50.7 | 19.06471 | 2.0 | 158.3 | 16.95 | 1.708 | 6.384 |




250
200
150
100
50
0
Time to surgery


Histogram
Frequency
50
45
40
35
30
25
20
15
10
5
0
[2, 10]
(10, 18]
(18, 26]
(26, 34]
(34, 42]
(42, 50]
(50, 58]
(58, 66]
(66, 74]
(74, 82]
(82, 90]
(90, 98]
(98, 106]
(106, 114]
(114, 122]
(122, 130]
(130, 138]
(138, 146]
(146, 154]
(154, 162]
Time from surgery to test




**Appendix C. RTS Test High Pass (≥95%) Frequencies**

| Test | Score | Frequency | Valid Percent (%) |
|---|---|---|---|
| **SLH LSI** | ≥95% | 83 | 63.4 |
| | <95% | 48 | 36.6 |
| **LH LSI** | ≥95% | 57 | 52.3 |
| | <95% | 52 | 47.7 |
| **SLVJ LSI** | ≥95% | 34 | 31.5 |
| | <95% | 74 | 68.5 |
| **DJ LSI** | ≥95% | 18 | 31.6 |
| | <95% | 39 | 68.4 |
| **Knee extension LSI** | ≥95% | 41 | 25.3 |
| | <95% | 121 | 74.7 |
| **Knee Flexion LSI** | ≥95% | 67 | 41.4 |
| | <95% | 95 | 58.6 |

**Appendix D. Secondary Analysis Outcome for Associations Between High Test Scores and RTS Status**

| Test | LSI Group | Full Return (n) | Partial Return (n) | Did Not Return / Changed Sport (n) | Total |
|---|---|---|---|---|---|
| **SLH LSI** | ≥95% | 24 (Exp: 22.6), 64.9% | 14 (Exp: 13.4), 63.6% | 17 (Exp: 18.9), 54.8% | 55 |
| | <95% | 13 (Exp: 14.4), 35.1% | 8 (Exp: 8.6), 36.4% | 14 (Exp: 12.1), 45.2% | 35 |
| **SLVJ LSI** | ≥95% | 9 (Exp: 8.4), 33.3% | 7 (Exp: 5.0), 43.8% | 7 (Exp: 9.6), 22.6% | 23 |
| | <95% | 18 (Exp: 18.6), 66.7% | 9 (Exp: 11.0), 56.3% | 24 (Exp: 21.4), 77.4% | 51 |
| **SLDJ LSI** | ≥95% | 3 (Exp: 2.5), 30.0% | 1 (Exp: 2.0), 12.5% | 5 (Exp: 4.5), 27.8% | 9 |
| | <95% | 7 (Exp: 7.5), 70.0% | 7 (Exp: 6.0), 87.5% | 13 (Exp: 13.5), 72.2% | 27 |
| **Knee Extension IKD LSI** | ≥95% | 7 (Exp: 9.8), 14.9% | 10 (Exp: 5.9), 35.7% | 6 (Exp: 7.3), 17.1% | 23 |
| | <95% | 40 (Exp: 37.2), 85.1% | 18 (Exp: 22.1), 64.3% | 29 (Exp: 27.7), 82.9% | 87 |
| **Knee Flexion IKD LSI** | ≥95% | 17 (Exp: 18.8), 36.2% | 9 (Exp: 11.2), 32.1% | 18 (Exp: 14.0), 51.4% | 44 |
| | <95% | 30 (Exp: 28.2), 63.8% | 19 (Exp: 16.8), 67.9% | 17 (Exp: 21.0), 48.6% | 66 |

**Appendix E. ACL-RSI Percentiles by RTS**

| RTS Category | 25th | Median | 75th |
|---|---|---|---|

| | | | |
|---|---|---|---|
| **Full Return** | 53 | 71.7 | 86.7 |
| **Moderate Return** | 38 | 50 | 70.3 |
| **Low Return** | 27.9 | 39 | 50.7 |
| **Unable to Return** | 34.5 | 47.5 | 60.4 |
| **Different Sport** | 48.3 | 80 | 91.7 |
| **Not Reported** | 41.4 | 60 | 83 |

**Appendix F. Knee Extension LSI Percentiles by Graft Type**

| Graft Type | 25th | Median | 75th |
|---|---|---|---|
| **Hamstring** | 83.33 | 90.84 | 96.22 |
| **BPTB** | 76.20 | 84.44 | 92.15 |
| **Quadriceps** | 74.29 | 85.76 | 92.30 |

**Appendix G. Knee Flexion LSI Percentiles by Graft Type**

| Graft Type | 25th | Median | 75th |
|---|---|---|---|
| **Hamstring** | 83.04 | 90.91 | 97.97 |
| **BPTB** | 85.43 | 95.88 | 104.99 |
| **Quadriceps** | 81.72 | 90.37 | 95.56 |

**Appendix H. Lateral Hop LSI Percentiles by RTS**

| RTS Category | 25th | Median | 75th |
|---|---|---|---|
| **Full Return** | 95.51 | 100.00 | 102.90 |
| **Moderate Return** | 87.61 | 97.24 | 102.94 |
| **Low Return** | 81.98 | 88.86 | 92.99 |
| **Unable to Return** | 80.41 | 92.27 | 104.21 |
| **Different Sport** | 74.24 | 90.08 | 100.00 |
| **Not Reported** | 83.78 | 93.04 | 101.87 |

**Appendix I. ACL-RSI Percentiles by Previous Ipsilateral Injury**

| Ipsilateral Injury | 25th | Median | 75th |
|---|---|---|---|
| **Yes** | 35 | 47 | 67.5 |
| **No** | 45 | 60 | 83 |

**Appendix J. ACL-RSI Percentiles by Lateral Tenodesis**

| Lateral Tenodesis | 25th | Median | 75th |
|---|---|---|---|
| **Yes** | 35 | 47.7 | 70 |
| **No** | 45 | 60 | 83 |

**Appendix K. Data Preparation and Analysis (SPSS)**

All data transformations and analyses were conducted in IBM SPSS Statistics (Version 30). Below is the complete annotated syntax demonstrating the reCoDing, labelling, and chi-square analyses used to address the study hypotheses

| Step | Syntax |
|---|---|
| **ReCoDe each RTS test variable into binary: 0 = <90%, 1 = ≥90%.** | RECODE SLHLSI (LOWEST THRU 89.999 = 0) (90 THRU HIGHEST = 1) INTO SLH_90.<br>RECODE SLVJLSI (LOWEST THRU 89.999 = 0) (90 THRU HIGHEST = 1) INTO SLVJ_90.<br>RECODE DJLSI (LOWEST THRU 89.999 = 0) (90 THRU HIGHEST = 1) INTO SLDJ_90.<br>RECODE IKDEXTLSI (LOWEST THRU 89.999 = 0) (90 THRU HIGHEST = 1) INTO IKD_EXT_90.<br>RECODE IKDFLEXLSI (LOWEST THRU 89.999 = 0) (90 THRU HIGHEST = 1) INTO IKD_FLEX_90.<br>EXECUTE. |
| **ReCoDe each test at 95% threshold to** | RECODE SLHLSI (LOWEST THRU 94.999 = 0) (95 THRU HIGHEST = 1) INTO SLH_95.<br>RECODE SLVJLSI (LOWEST THRU 94.999 = 0) (95 THRU HIGHEST = |

| | |
|---|---|
| **examine high performance cutoffs.** | 1) INTO SLVJ_95.<br>RECODE DJLSI (LOWEST THRU 94.999 = 0) (95 THRU HIGHEST = 1) INTO SLDJ_95.<br>RECODE IKDEXTLSI (LOWEST THRU 94.999 = 0) (95 THRU HIGHEST = 1) INTO IKD_EXT_95.<br>RECODE IKDFLEXLSI (LOWEST THRU 94.999 = 0) (95 THRU HIGHEST = 1) INTO IKD_FLEX_95.<br>EXECUTE. |
| **Label these high threshold variables similarly.** | VARIABLE LABELS SLH_95 'SLH LSI ≥95%' SLVJ_95 'SLVJ LSI ≥95%' SLDJ_95 'SLDJ LSI ≥95%' IKD_EXT_95 'Knee Extension IKD LSI ≥95%' IKD_FLEX_95 'Knee Flexion IKD LSI ≥95%'. VALUE LABELS SLH_95 SLVJ_95 SLDJ_95 IKD_EXT_95 IKD_FLEX_95 0 'Below 95%' 1 '95% or Above'. |
| **Examine association with full 5-category RTS outcomes.** | CROSSTABS /TABLES=SLH_95 BY RTS /STATISTICS=CHISQ /CELLS=COUNT EXPECTED ROW COLUMN.<br>CROSSTABS /TABLES=SLVJ_95 BY RTS /STATISTICS=CHISQ /CELLS=COUNT EXPECTED ROW COLUMN.<br>CROSSTABS /TABLES=SLDJ_95 BY RTS /STATISTICS=CHISQ /CELLS=COUNT EXPECTED ROW COLUMN.<br>CROSSTABS /TABLES=IKD_EXT_95 BY RTS /STATISTICS=CHISQ /CELLS=COUNT EXPECTED ROW COLUMN.<br>CROSSTABS /TABLES=IKD_FLEX_95 BY RTS /STATISTICS=CHISQ /CELLS=COUNT EXPECTED ROW COLUMN. |
| **Group RTS into 3 Categories for Valid Chi-Square Analysis Regroup RTS: 1 = Full, 2+3 = Partial, 4+5 = Did Not Return / Changed Sport.** | RECODE RTS (1 = 1) (2 3 = 2) (4 5 = 3) INTO RTS_grouped.<br>VARIABLE LABELS RTS_grouped 'RTS Outcome Grouped: 1=Full, 2=Partial, 3=Did not return/Changed sport'.<br>VALUE LABELS RTS_grouped 1 'Full Return' 2 'Partial Return' 3 'Did Not Return / Changed Sport'.<br>EXECUTE. |
| **Testing association between ≥95% LSI performance and RTS outcomes.** | CROSSTABS /TABLES=SLH_95 BY RTS_grouped /STATISTICS=CHISQ /CELLS=COUNT EXPECTED ROW COLUMN.<br>CROSSTABS /TABLES=SLVJ_95 BY RTS_grouped /STATISTICS=CHISQ /CELLS=COUNT EXPECTED ROW COLUMN. |

| | |
|---|---|
| | CROSSTABS /TABLES=SLDJ_95 BY RTS_grouped /STATISTICS=CHISQ /CELLS=COUNT EXPECTED ROW COLUMN.<br>CROSSTABS /TABLES=IKD_EXT_95 BY RTS_grouped /STATISTICS=CHISQ /CELLS=COUNT EXPECTED ROW COLUMN.<br>CROSSTABS /TABLES=IKD_FLEX_95 BY RTS_grouped /STATISTICS=CHISQ /CELLS=COUNT EXPECTED ROW COLUMN. |
| **Additional tests using ≥90% thresholds.** | CROSSTABS /TABLES=SLH_90 BY RTS_grouped /STATISTICS=CHISQ /CELLS=COUNT EXPECTED ROW COLUMN.<br>CROSSTABS /TABLES=SLVJ_90 BY RTS_grouped /STATISTICS=CHISQ /CELLS=COUNT EXPECTED ROW COLUMN.<br>CROSSTABS /TABLES=SLDJ_90 BY RTS_grouped /STATISTICS=CHISQ /CELLS=COUNT EXPECTED ROW COLUMN.<br>CROSSTABS /TABLES=IKD_EXT_90 BY RTS_grouped /STATISTICS=CHISQ /CELLS=COUNT EXPECTED ROW COLUMN.<br>CROSSTABS /TABLES=IKD_FLEX_90 BY RTS_grouped /STATISTICS=CHISQ /CELLS=COUNT EXPECTED ROW COLUMN. |