

**Cleared But Not Ready? The Impact of Fatigue on Return-To-Sport
Testing Post Anterior Cruciate Ligament Injury.**

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Abstract:

Anterior cruciate ligament (ACL) injury is associated with prolonged rehabilitation, substantial healthcare costs, reduced sports participation, and an elevated risk of reinjury after return to sport (RTS). Despite routine RTS testing to guide clinical decisions after ACL injury and reconstruction, reinjury rates remain high, suggesting current assessments may not adequately evaluate readiness for sport demands. Most RTS assessments are done in a rested state, although fatigue is an inherent feature of sport that alters neuromuscular control, movement quality, force production, and landing mechanics. These effects may be especially relevant in female athletes, who have higher rates of non-contact ACL injury and already exhibit higher-risk movement patterns that fatigue may further compromise. Consequently, athletes may meet RTS criteria when rested but show deficits under fatigue. This thesis investigated fatigue's influence on ACL RTS assessment and explored whether fatigue-informed testing identifies deficits missed during conventional rested evaluations.

To address this aim, two studies were conducted. The first, a scoping review, evaluated fatigue protocols used in ACL RTS research regarding clinical relevance, feasibility, and translational potential. Twelve studies were identified, with protocols classified as localised neuromuscular ($n = 7$), whole-body sport-specific ($n = 4$), or isolated joint ($n = 1$). Fatigue consistently reduced absolute hop and jump performance, movement quality, and biomechanical variables linked to ACL injury risk. However, substantial heterogeneity existed across fatigue definitions, induction methods, verification criteria, and RTS assessment batteries. Notably, limb symmetry indices often remained unchanged despite reductions in absolute performance, suggesting symmetry-based measures may mask bilateral functional declines and underestimate fatigue-related deficits.

The second study, a repeated-measures experiment, examined fatigue's acute effects on RTS outcomes in 15 recreationally active female athletes (23.1 ± 4.7 years). Healthy participants were recruited to isolate fatigue effects without the confounding influence of ACL injury or rehabilitation. Participants completed a standard RTS testing battery under rested and fatigued conditions. Fatigue was induced through repeated hopping, jumping, squatting, and step-down tasks until countermovement jump height dropped by at least 30%. After fatigue, quadriceps strength decreased by 9.8% ($p < .001$) and single-leg hop distance by 17.3% ($p = .041$). While most traditional RTS outcomes and limb symmetry measures remained unchanged, force-time-derived kinetic variables showed consistent reductions, including eccentric peak force, eccentric braking impulse, concentric impulse, and landing rate of force development.

Collectively, these findings indicate fatigue can reveal neuromuscular and biomechanical impairments not detected by conventional RTS assessment done in a rested state. Traditional RTS measures retain clinical value but may not fully reflect functional capacity under physiological stress. Fatigue-informed assessment, especially through kinetic measures, can identify residual neuromuscular deficits concealed during conventional RTS testing. Further research is needed to establish clinically feasible fatigue protocols in ACL-reconstructed populations and determine whether fatigue-related RTS outcomes improve prediction of successful return to sport and reinjury risk.

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Attestation of Authorship

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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 was 25/248, with approval granted on the 20th of August 2025 (Appendix 1).

Chapter 1: Introduction

1.1 Background

1.1.1 Defining the Issue

The anterior cruciate ligament (ACL) is critical for knee stability during high-demand athletic activities. It limits anterior tibial translation and rotational forces, enabling athletes to absorb load, change direction, and maintain joint integrity in dynamic conditions^{1,2}. Most ACL injuries result from non-contact mechanisms, typically due to insufficient kinetic and kinematic control during movement^{3–5}. Ruptures commonly occur during rapid deceleration, directional changes on a planted foot, pivoting, or ineffective landing. ACL injury is multifactorial, involving sub-optimal movement patterns as well as physiological and psychological factors affecting task execution⁶.

ACL rupture is one of the most common and clinically significant knee injuries in sport, particularly in field and court disciplines¹. Global incidence ranges from 68.8 to 81 per 100,000 in the general population, with an estimated 100,000–200,000 cases occurring annually among competitive athletes⁷. Complete ruptures typically require surgical reconstruction followed by prolonged rehabilitation. Recovery duration varies according to pre-injury strength, injury characteristics, surgical technique, and concomitant injuries such as meniscal or collateral ligament damage^{8–13}. Return to sport (RTS) may occur as early as six months post-surgery, although many athletes require twelve months or longer, and rehabilitation timelines remain poorly standardised. Consequently, all these factors attribute to varying reported RTS success rates from 50% to 90%¹⁴, as well as highlighting the complexity of recovery and the potentially substantial burden associated with ACL injury.

In New Zealand, ACL injuries represent a considerable burden on both the healthcare system and sporting populations. Between 2009 and 2016, Accident Compensation Corporation (ACC) (New Zealand's no-fault national injury incidence insurance scheme) data recorded 20,751 primary ACL reconstructions (ACLR), corresponding to an annual incidence of 58.3 per 100,000 person-years, with incidence increasing by 11% over that period¹⁵. Incidence was substantially higher in males than females (72.2 versus 44.9 per 100,000). Peak incidence occurred in males aged 20–24 years and females aged 15–19 years; notably, incidence among females aged 15–19 years increased from 125.3 per 100,000 during 2009–2012 to 165.2 per 100,000 during 2013–2016¹⁵. Sporting injuries accounted for 76% of

ACLR cases, with netball, rugby union, and football responsible for the greatest proportion of sport-related injuries¹⁵.

ACL injuries also impose substantial economic and clinical costs, with the greatest burden falling on the 20-25-year-old population. The ACC funds surgical, rehabilitation and occupation compensation services for ACL injuries, spending more than \$25 million annually on ACL surgery while expensing associated ongoing physiotherapy exceeding \$100 million per year across all injury types¹⁶. Recent ACC claims data indicate that this burden continues to increase. Between 2015 and 2024, ACC accepted 31,745 new ACL injury claims, with annual claims rising from 3,016 to 3,866¹⁷. Over the same period, the active cost of ACL injury claims (excluding GST) increased from \$61.1 million to \$157.2 million annually, with total expenditure exceeding \$930 million¹⁷. Soccer, rugby union, and netball remained the sport's most frequently associated with ACL injury claims, and the majority of claims occurred among individuals aged 15–34 years¹⁷. Despite this investment, physiotherapy utilisation following ACL injury remains inconsistent. Eighty-one per cent of claimants received fewer than 15 ACC-funded physiotherapy sessions during the first 12 months following injury or surgery, while 13% received none, despite best-practice guidelines recommending 21–35 sessions¹⁶.

Following rehabilitation, individuals with a previous ACL injury often exhibit persistent physical and psychological deficits, including reduced strength, altered movement mechanics, diminished confidence, and increased fear of reinjury^{18,19}. These impairments may compromise performance and increase reinjury risk. Despite advances in surgical techniques and structured rehabilitation, reinjury rates remain high. Meta-analyses report that up to 30% of athletes sustain a second ACL injury, encompassing both graft rupture (ipsilateral) and contralateral ACL injury, with rates of 25–33% among younger athletes in multidirectional team sports^{20–22}. Winkler et al.²² reported that 20% of athletes sustained an ipsilateral graft rupture and 13% a contralateral ACL injury within twelve months post ACLR. By comparison, concomitant medial and lateral meniscus injuries were present in 24% and 28% of the cohort, respectively.

These findings suggest persistent limitations in rehabilitation and RTS decision-making. Likewise, re-injury rate may be explained by the absence of consistent ecologically valid, evidence-based criteria for determining RTS readiness^{14,23}. Highlighting a potential need to determine more robust/ecological valid objective measurements of movement to assess RTS readiness. The following sections examine female athletes as an elevated risk population, current RTS assessment frameworks, and the potential influence of fatigue on movement quality and RTS decision-making.

1.1.2 Female Athletes and Elevated ACL Risk

Female athletes are a priority population for ACL research because their risk of injury per unit of sporting exposure is higher than that of males. Within New Zealand, ACLR incidence calculated against the general population is higher in males than females (72.2 vs. 44.9 per 100,000), but because males participate in sport at substantially higher rates, these figures likely underestimate female risk relative to playing exposure. When adjusted for activity level, females generally demonstrate a greater risk of ACL injury per exposure than males¹⁵. The burden is also rising in young females, where peak reconstruction rates occur in females aged 15-19 years (compared with 20-24 years in males), and incidence in this group increased from 125.3 per 100,000 during 2009-2012 to 165.2 per 100,000 during 2013-2016, a 32% increase in less than a decade¹⁵.

Female athletes have a higher risk of ACL injury than males in comparable sporting environments. This increased risk reflects anatomical, physiological, and neuromuscular factors that likely effect mechanical demands and capability during high-risk movements. Females typically present with a narrower intercondylar notch, smaller ACL cross-sectional area, greater quadriceps (Q) angle, and steeper tibial slope, all of which are associated with increased ACL loading during dynamic tasks²⁴. Biomechanically, females more frequently display movement patterns associated with non-contact ACL injury, including greater dynamic knee valgus, reduced hip and knee flexion at initial contact, and diminished trunk control during cutting and landing tasks²⁵. These movement patterns are central to the mechanism of non-contact ACL rupture²⁶.

These biomechanical risk factors may be further exacerbated under physical load. In healthy populations, fatigue deteriorated landing mechanics, with a notable proportion of participants shifting from low- to high-risk LESS categories after exercise²⁷. Females demonstrated higher landing error scores than males at both rested and fatigued time points, although the fatigue*sex interaction has not shown significant in prior research²⁷. Therefore, suggesting that fatigue may further compromise landing mechanics in a population already exhibiting biomechanical differences²⁷. This is particularly relevant to RTS decision-making, as assessments conducted under rested conditions may fail to identify deficits that emerge during competition.

The combination of elevated baseline risk and the effect of fatigue on landing mechanics makes female athletes a key population in ACL injury prevention and rehabilitation. Consequently, limitations in current RTS frameworks may have the greatest impact in athletes who already exhibit higher-risk movement patterns and in whom fatigue may further compromise landing mechanics. The following

sections examine current RTS assessment frameworks before considering the role of fatigue in exposing deficits not detected during rested assessments.

1.1.3 The Role of Return-to-Sport Testing

The purpose of RTS testing is to determine whether an athlete possesses sufficient physical, biomechanical, and psychological readiness to safely resume sport participation. RTS decision-making therefore represents a critical stage of ACL rehabilitation, where premature clearance may increase reinjury risk^{28,29}. Current RTS approaches may not fully capture the dynamic, fatigued, and reactive nature of competitive sport. In particular, existing assessment methods rarely account for fatigue, an athlete's endurance capacity, or fatigue-related changes in movement quality³⁰. Consequently, assessments conducted exclusively under rested, controlled conditions may fail to identify functionally relevant deficits, increasing the likelihood that athletes are cleared despite being inadequately prepared for real-world sport.

RTS testing typically evaluates readiness across multiple domains. Muscular strength is commonly assessed using isokinetic dynamometry (in laboratory environments), while hop tests are used as indirect indicators of functional performance and tolerance to repeated loading^{31–33}. Muscular endurance is rarely assessed directly and is instead inferred from performance decline across repeated trials. Movement quality is typically evaluated through observational screening of gross functional tasks (e.g., squat, jump-landing, or single-leg balance screens) rather than direct assessment of the neuromuscular coordination underlying movement control, such as surface electromyography, three-dimensional motion capture, or force plate analysis of joint kinetics and muscle activation timing. Self-reported psychological readiness is commonly included as a fourth domain. Common assessment tools include isokinetic strength testing, single- and triple-hop tests, the Limb Symmetry Index (LSI), and patient-reported outcome measures¹⁴. Together, these assessments aim to provide a comprehensive picture of recovery.

More than 30 RTS assessment batteries have been described, with considerable variation in test selection, performance thresholds, and clinical application¹⁴. Many clinics use local protocols, meaning the combination of tests, cut-off scores defining readiness, and weighting of individual domains differ substantially between settings. Regardless of the assessment battery used, RTS decisions are typically made under non-fatigued, controlled conditions that may not reflect the physiological demands of competitive sport^{30,34}. Consequently, RTS criteria remain both inconsistent and potentially insufficient for determining readiness to return to sport.

Reported rates of athletes returning to their pre-injury level of performance remain low, with up to 50% failing to regain their previous level of competition^{14,35}. Furthermore, meeting commonly applied RTS criteria does not eliminate the risk of subsequent ACL injury. Graft rupture has been reported in up to 16.5% of athletes despite satisfying all objective discharge criteria³⁶, and reinjury rates of up to 5.6% have also been documented following successful completion of standard RTS testing³⁷. This suggests that current RTS thresholds may lack the sensitivity to identify persistent neuromuscular and biomechanical deficits that are not evident during rested testing. Collectively, these findings raise a fundamental question: if athletes are meeting RTS criteria yet continue to sustain reinjury, what aspects of readiness are current assessments failing to detect?

1.1.4 Fatigue as a Component of RTS Decision-Making

Part of the explanation for the limitations of current RTS decision-making may lie in the conditions under which assessments are performed. RTS testing is typically conducted in controlled, non-fatigued environments²³, despite competitive sport being characterised by progressive physiological and cognitive demands. Emerging evidence suggests that fatigue may exacerbate neuromuscular deficits and impair movement coordination in ways that are not evident during rested assessments^{30,38}. Consequently, evaluating athletes exclusively under non-fatigued conditions may overestimate readiness to return to sport²³, increasing exposure to reinjury risk. This discrepancy between clinical testing and competitive sport highlights the need to better understand how fatigue influences neuromuscular performance and movement quality.

Acute and accumulated fatigue have been associated with alterations in lower-limb biomechanics, sensorimotor control, landing strategies, and force-production characteristics that resemble recognised ACL injury risk factors^{39–41}. Reported changes include reduced hip and knee flexion, increased dynamic knee valgus, diminished eccentric braking capacity, greater inter-limb asymmetry during cutting and landing tasks^{39–41}, and impaired trunk control resulting in greater centre of mass sway during multidirectional movement⁴². Collectively, these findings suggest that fatigue influences not only physical performance but also movement strategy. Rather than simply producing less force, fatigued athletes may adopt stiffer landing strategies, greater frontal-plane knee motion, or increased reliance on the uninvolved limb, potentially increasing mechanical loading on the knee^{38,43,44}. Although these adaptations are not direct mechanisms of ACL injury, they reflect movement characteristics consistently associated with increased injury risk³.

Relatively few studies have investigated the influence of fatigue on RTS performance following ACL reconstruction^{30,38,45}. Tallard et al.³⁰ induced fatigue using repeated circuits of squats, single-leg box jumps, countermovement jumps, and sprints until participants could no longer achieve 70% of their maximal countermovement jump height. Under fatigued conditions, participants demonstrated impairments in hop performance, force production, and movement quality that were less apparent during rested testing, suggesting that fatigue may reveal deficits overlooked by conventional RTS assessments. Similarly, van Melick et al.³⁸ used a one-hour soccer-specific training session to induce fatigue before assessing landing quality using the Landing Error Scoring System. Although hop and jump performance outcomes did not differ between groups, movement quality deteriorated substantially in the ACLR group, with 86% failing the movement quality criterion compared with 32% of healthy controls; a difference not observed under rested conditions. Wesley et al.²⁷ likewise reported increased landing errors following a functional fatigue protocol incorporating sprinting, jumping, and cutting tasks. Females demonstrated higher landing error scores than males throughout testing, suggesting fatigue may further compromise landing mechanics in populations already exhibiting biomechanical differences²⁷.

Collectively, these findings indicate that conventional RTS assessments performed under rested conditions may fail to detect deficits that emerge following fatigue, particularly during tasks requiring repeated force production, dynamic stabilisation, and neuromuscular coordination. However, despite this emerging evidence, no consensus exists regarding how fatigue should be incorporated into clinical assessment or RTS decision-making, and standard RTS testing continues to be performed under non-fatigued conditions. The scope of this literature, and the extent to which existing fatigue protocols reflect the demands of competitive sport, is explored in the scoping review presented in Chapter 2.

1.2 Rationale, Purpose, and Thesis Structure

RTS after ACL injury is essential in rehabilitation, but re-injury rates remain high and functional deficits often persist even when athletes meet standard RTS criteria. Fatigue may contribute to these outcomes. Athletes re-enter competition environments with significant physical and cognitive demands that increase fatigue, yet the influence of fatigue on ACL RTS assessment and clinical decision-making remains unclear. This thesis addresses this gap.

This work addresses two primary limitations in the literature. First, studies examining fatigue in ACL RTS testing employ heterogeneous protocols, including aerobic exercise, sport-specific drills, strength tasks, and plyometrics. No synthesis exists to determine which protocols most accurately replicate fatigue states while remaining feasible for clinical use. Assessment immediately post-match may offer the most ecologically valid fatigue state, but is often impractical due to constraints of time, equipment, space, staffing, and athlete risk. As a result, clinicians require protocols that balance ecological validity with feasibility. The absence of standardisation restricts the selection of protocols that are both representative of sporting demands and practical to implement. Second, although individual studies report that fatigue can alter hop performance, ground-reaction forces, joint kinematics, and movement quality, there is no consensus regarding the effects of acute fatigue on kinetic outcomes across RTS tests or the sensitivity of specific variables to fatigue. These gaps question whether current RTS assessments reflect the fatigue conditions experienced by athletes on return to sport.

This thesis addresses these limitations through two complementary studies. Study 1 is a scoping review that maps fatigue protocols in ACL RTS research, evaluating definitions, applications, clinical relevance, and feasibility. Study 2 is an experimental study examining the effects of a clinically relevant and feasible fatigue protocol on outcomes of common RTS tests. The findings aim to inform ecologically valid RTS testing and improve clinical interpretation under fatigued conditions.

1.3 Research Questions

This thesis is guided by the following research questions:

1. What fatigue protocols have been used in studies examining anterior cruciate ligament return-to-sport testing?
2. Are previously used fatigue protocols within anterior cruciate ligament return-to-sport clinically feasible and ecologically valid?
3. How does acute fatigue affect kinetic outcomes during commonly administered RTS hop and jump tests?

1.4 Thesis Structure

This thesis follows the Pathway 2 structure and is organised into four chapters that collectively address the research aims and objectives (Figure 1). In line with Auckland University of Technology guidelines, Chapters Two and Three are prepared for journal publication and presented in the format required by

their intended journals, resulting in some unavoidable repetition. Each chapter opens with a prelude that clarifies its relationship to the others and situates the work within the broader thesis narrative.

Chapter 1 establishes the rationale and context for the research, identifying the key gaps in the literature and articulating the aims that guide the work. Chapter 2 presents a scoping review designed to map and critically evaluate how fatigue is incorporated into ACL RTS testing, with particular attention to the types of protocols used and the degree to which they reflect real-world athletic/clinical demands. Chapter 3 reports an acute experimental study examining how a proposed clinically relevant, sport-specific fatiguing protocol influences performance on commonly used RTS tests, with a focus on kinetic outcomes. Chapter 4 integrates the findings from both studies to generate practical recommendations for clinicians regarding the role of fatigue in ACL RTS testing. This final chapter also presents a discussion of the thesis's strengths, limitations, and directions for future research.

Cleared But Not Ready? The Impact of Fatigue on Return-To-Sport Testing Post Anterior Cruciate Ligament Injury.

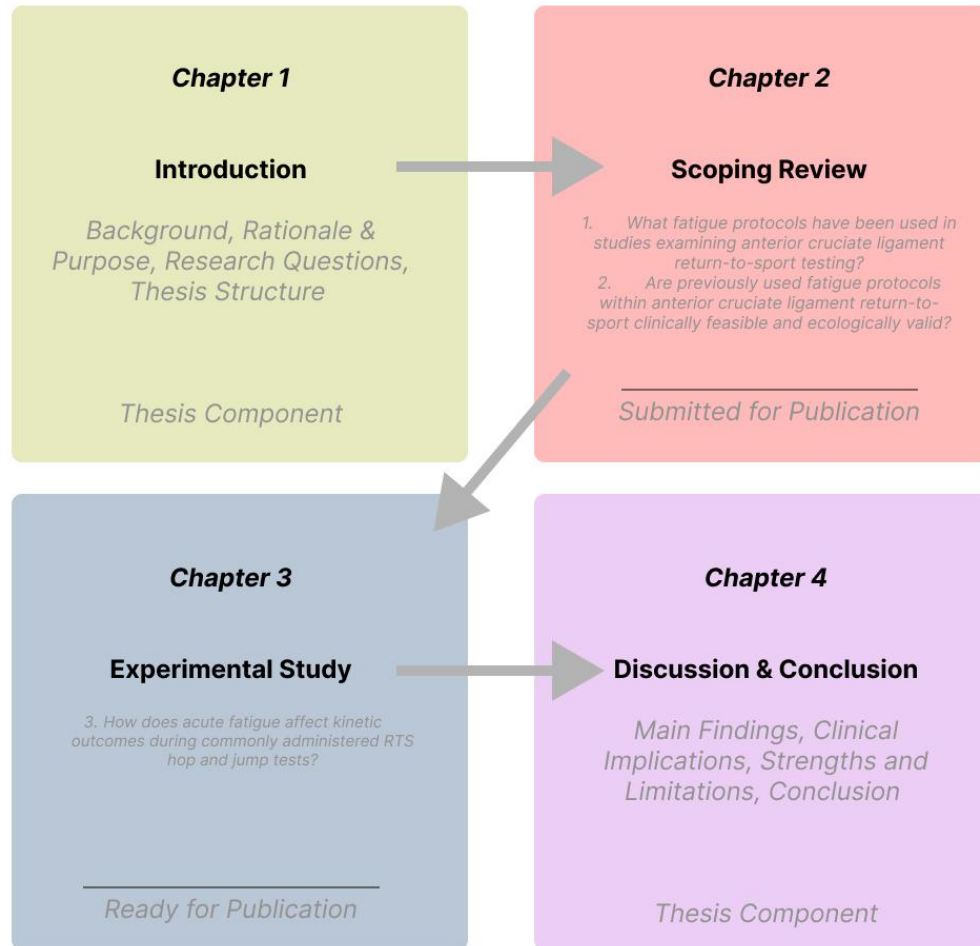


Figure 1. A Graphic diagram of the thesis structure and included papers

Prelude to Chapter 2

In order to integrate fatigued return-to-sport decision-making for athletes following ACL reconstruction, there must first be a clear understanding of what fatigue protocols are currently described in the literature, and how clinically relevant they are for rehabilitation and sports medicine practice. This chapter takes the form of a scoping review to map and evaluate the fatigue protocols used in ACL RTS

testing, with a focus on their feasibility, clinical applicability, and alignment with real-world sport demands. A scoping review was deemed most appropriate to map the current landscape of this area, identify gaps in the literature, and determine priorities for future research⁴⁶.

Chapter 2: Clinically Relevant Fatigue Protocols in Return-to-Sport Testing Post Anterior Cruciate Ligament Injury. A Scoping Review

2.1 Abstract

Objective: To outline the fatigue protocols used with ACL RTS assessments, evaluate their clinical relevance, and identify gaps to inform future research and clinical practice.

Design: Scoping Review

Literature search: Scopus, Medline, PubMed, SPORTDiscuss, and CINHALL were searched on 18 November 2025 without date restriction. References were manually checked and forward citation tracking was conducted using Google Scholar.

Study selection criteria: Peer-reviewed primary research using an induced fatigue protocol with biomechanical, physiological, or performance-based RTS outcomes in ACLR or healthy athletic populations.

Data synthesis: Study characteristics, fatigue protocol design, RTS test batteries, and outcome measures were extracted using a standardised charting form. Fatigue protocols were categorised by physiological domain. Clinical feasibility was assessed using a structured synthesis framework.

Results: Twelve studies published between 2014 and 2025 were included. Fatigue protocols were classified as localised neuromuscular (n=7), whole-body sport-specific (n=4), or isolated joint (n=1). Fatigue reduced absolute hop and jump performance bilaterally across all protocols/populations. Limb symmetry index remained stable in several studies despite this bilateral decline, suggesting that symmetry-based metrics alone may mask overall functional deterioration under fatigue. Four studies reported post-fatigue kinematic and kinetic changes, including reduced knee flexion, increased frontal-plane loading, and increased lower-limb stiffness. Movement quality, measured by the Landing Error Scoring System, declined post-fatigue in all three studies using this assessment.

Conclusion: Fatigue reveals functional and biomechanical deficits not observed under rested RTS assessment conditions. Protocol heterogeneity limits cross-study comparison and clinical application. Standardised, feasible fatigue protocols validated within established RTS frameworks are required.

2.2 Introduction

The anterior cruciate ligament (ACL) is critical for knee stability during multidirectional sport, resisting anterior tibial translation and rotational forces, particularly during cutting, pivoting, and deceleration^{1,25}. This underpins load absorption and rapid directional change during sport. ACL injury is often debilitating, leading to prolonged rehabilitation, psychological burden, and disrupted sporting participation^{4,47}. ACL injuries occur in approximately 1 in 29 female and 1 in 50 male athletes per season, with ruptures predominantly resulting from non-contact mechanisms involving sudden deceleration, jump landing, and rapid directional change on a planted foot³⁻⁵. Poor neuromuscular control and biomechanics, including excessive knee valgus and trunk instability, increase injury risk during these movements^{6,7}. Female athletes have a 3-6 times higher injury rate, attributed to sex-specific anatomical, biomechanical, hormonal, and neuromotor factors that are believed to increase ACL vulnerability under high physiological demand⁴⁸.

Return-to-sport (RTS) testing is central to post-ACL reconstruction (ACLR) rehabilitation, informing readiness decisions for sport⁴⁹. Current RTS assessments focus on strength symmetry, hop performance, and psychological readiness, but are typically conducted under controlled, non-fatigued conditions, limiting clinical utility. Competitive sport imposes sustained physiological/biomechanical load, requiring neuromuscular control under fatigue^{44,50}. Fatigue impairs neuromuscular control, alters movement patterns, and increases the risk of ACL injury^{51,52}. Consequently, deficits in movement quality and functional performance may go undetected, as rested-state testing fails to replicate the physiological demands of competitive play.

Recent studies have incorporated fatigue into RTS testing using protocols such as plyometric circuits^{27,30,43}, step-down tasks^{27,45}, and hop-based assessments^{45,53}. However, substantial heterogeneity exists, with protocols varying in task type, intensity, duration, and sport specificity, complicating comparison and limiting clinical translation. In addition, the conceptualisation of fatigue is inconsistent, with protocols spanning peripheral, central, cardiovascular, and metabolic domains⁵⁴. This inconsistency likely produces different responses, often treated as equivalent in the literature^{44,51}. Such

methodological and conceptual inconsistency challenges the integration of fatigue into RTS assessment in clinical practice.

Despite evidence on fatigue's effects in ACL RTS testing, variability in findings and methodology has limited systematic understanding of how fatigue influences RTS outcomes and its clinical feasibility. This review outlines fatigue protocols used in ACL RTS assessments, evaluates their clinical relevance, and identifies gaps to inform future research and practice. A scoping review was selected based on preliminary evidence assessment.

2.3 Methods

The review was conducted in accordance with Arksey and O'Malley's framework⁵⁵, and reporting adhered to the Preferred Reporting Items for Systematic Review and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines⁵⁶. The research questions, eligibility criteria, and data charting approach were developed following Joanna Briggs Institute guidance⁵⁷, which informed study selection, data extraction, and synthesis. Review methods were established *a priori*; protocol registration via the Open Science Framework was completed retrospectively. The search strategy was developed by all authors and employed Boolean logic to combine keywords related to ACL RTS testing and fatigue protocols. An initial search string was created for PubMed and adapted for each database to account for differences in indexing terms and syntax. The search was conducted across five databases (PubMed, MEDLINE, Scopus, SPORTDiscus, and CINAHL) on November 18, 2025, without publication date restrictions. Reference lists of included studies and relevant reviews were manually screened, and forward citation tracking was performed using Google Scholar to identify previously unidentified studies. All searches were limited to English-language publications. An example of a search string used in PubMed was: ('anterior cruciate ligament' OR 'ACL') AND ('return to sport' OR 'RTS' OR 'functional testing') AND ('fatigue' OR 'exercise-induced fatigue' OR 'fatigue protocol').

Eligibility criteria were established using the Population, Concept, Context (PCC) framework⁵⁷. The population included individuals undergoing ACL RTS testing, either injured or healthy. The concept focused on the influence of a pre-RTS fatigue protocol on relevant outcomes. The context was restricted to clinically applicable settings. Studies were included if they reported data on the impact of induced fatigue on biomechanical, physiological, or performance-based outcomes relevant to RTS. Only peer-reviewed primary research articles were considered (Table 1).

Table 1. Study inclusion and exclusion criteria

Inclusion	Exclusion
Studies involving individuals undergoing ACL return-to-sport (RTS) testing, including those with ACL reconstruction (ACLR) or injury history	Studies that do not include a fatigue protocol as part of RTS testing
Studies that describe or apply fatigue protocols in conjunction with RTS testing (neuromuscular, functional, or cardiovascular)	<i>Reviews, commentaries, or editorials (though their reference lists were screened)</i>
Clinical, rehabilitation, or sports medicine settings, including laboratory-based studies with clinical implications	Animal Studies
Peer-reviewed primary research (experimental, observational), grey literature (e.g., clinical guidelines, conference abstracts)	Non-English language
English language	Studies focused solely on fatigue in general performance testing without RTS relevance

References were downloaded to the Rayyan reference management platform⁵⁸, where duplicates were removed as a first step. Initial title and abstract screening were conducted by the primary author, followed by full-text screening, before being confirmed by third author to determine final study inclusion. The secondary author was available to resolve discrepancies through discussion; however, this was not required.

Data charting was undertaken using a standardised extraction form (Microsoft Excel⁵⁹) recording study design, participant characteristics, fatigue protocol details, RTS testing, primary study outcomes, secondary biomechanical measures, the Limb Symmetry Index (LSI) and the Landing Error Scoring System (LESS) (when reported). LSI is calculated as the involved limb's performance expressed as a percentage of the uninvolved limb's performance⁶⁰. The Landing Error Scoring System (LESS), an observational tool scoring movement quality during a standardised landing task, where higher scores indicate more errors and a score of ≥ 6 denotes high-injury-risk landing mechanics⁶¹. Furthermore, Clinical feasibility indicators (equipment, time, applicability to clinical/sport settings) were also recorded.

2.3.1 A Novel Clinical Feasibility Framework

A clinical feasibility framework was developed to compare fatigue protocols according to their potential for clinical implementation (Table 5). The framework prioritises pragmatic characteristics relevant to clinical translation and does not assess methodological quality or risk of bias. It was applied independently of study quality and used as a descriptive synthesis tool for structured comparison across studies.

Fatigue protocols were evaluated across four domains: equipment requirements, protocol duration, setting suitability, and ecological validity. *Equipment requirements* referred to the physical resources

and technology needed, from standard to laboratory-grade. *Protocol duration* is considered the time required to induce fatigue within clinical constraints. *Setting suitability* assessed the appropriateness of clinical environments for implementation. *Ecological validity* measured how closely the fatigue stimulus replicated the physiological and biomechanical demands of sport.

Each domain was assessed against a feasibility benchmark relevant to outpatient physiotherapy or sports clinic settings, with one star assigned per criterion met. *Equipment requirements* received a star if only standard outpatient resources were needed. *Protocol duration* was awarded a star if fatigue could be induced within a standard clinical appointment. *Setting suitability* received a star if no dedicated sports or laboratory facilities were required. *Ecological validity* was recognised if the fatigue stimulus reflected sport-relevant physiological or biomechanical demands. Composite feasibility scores ranged from 0 to 4 stars, with higher scores indicating greater feasibility for standard clinical and sport settings.

2.4 Results

2.4.1 Study Selection and Participant Characteristics

A total of 1,927 records were retrieved for title and abstract review following the removal of 105 duplicates from an initial yield of 2,032, with 12 studies satisfying the inclusion criteria and included in the final synthesis (Figure 2 and Table 2). The publication dates ranged from 2014 to 2025, with seven (58%) of the included studies published since 2019.

Apart from White et al.⁴⁵, who used a randomised crossover design, all reviewed studies were cross-sectional in nature. Participant sample size ranged from 12⁶² to 80⁵³, with a median of approximately 35. Six studies included ACLR participants as the primary or sole group^{30,34,38,43,50,63}, five recruited healthy athletes only^{27,45,62,64,65}, and six included both ACLR and healthy cohorts as separate groups^{34,38,43,50,53,63}. For post-ACLR populations, the post-surgical timing of assessment ranged from a mean of 6 months⁵³ to 3.9 years³⁴. Sex distribution was often unequal; pooled across studies, males outnumbered females (n = 275 vs. n = 232). Only two studies examined a single sex cohort^{38,62}, and only Wesley et al.²⁷ analysed sex as an independent variable.

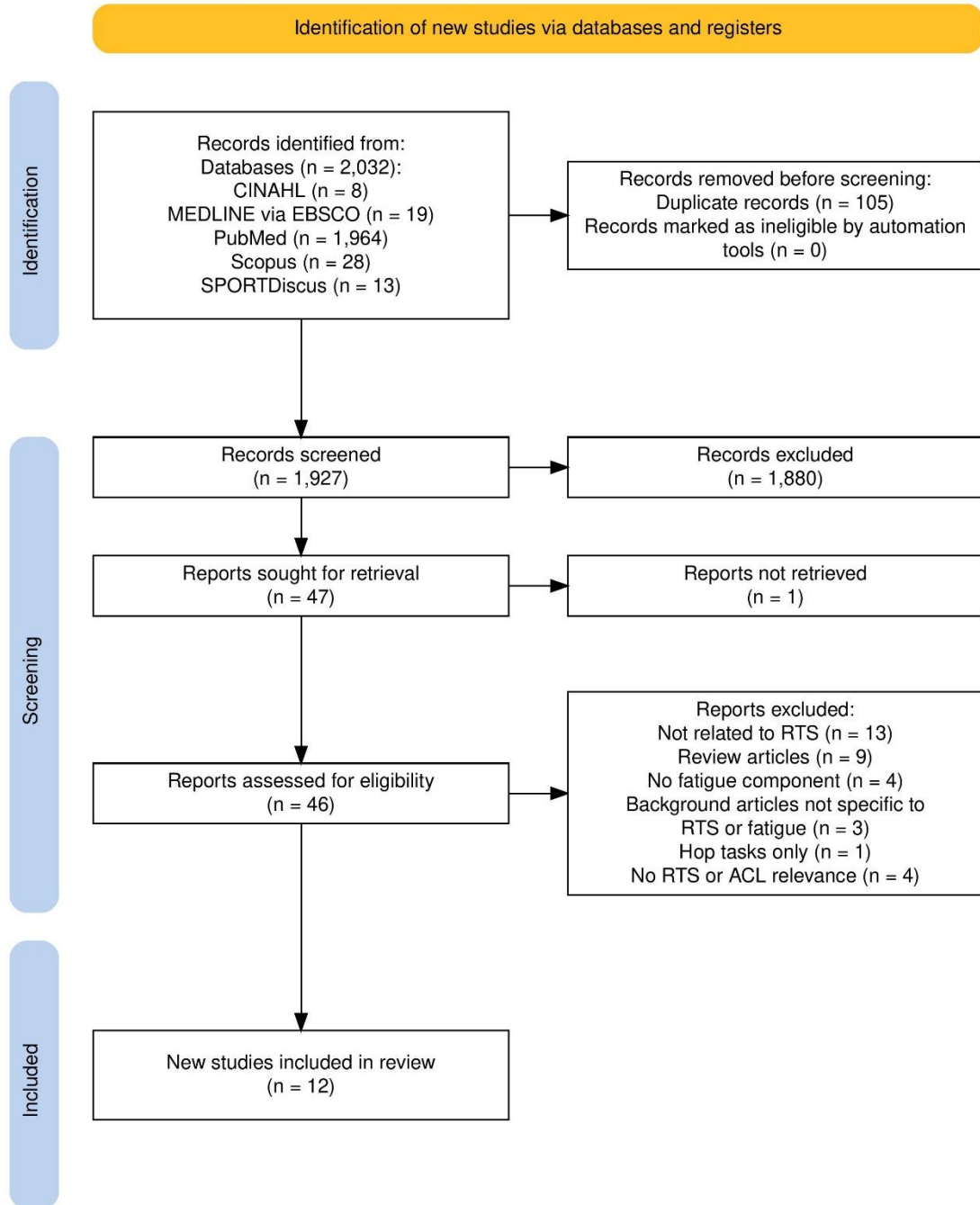


Figure 2. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram

Table 2. Study design and participant characteristics

Author (Year)	Study Design	Population	Sex (N)	Mean Age (Y)	Time post-ACLR	Setting
Tallard et al. ³⁰	Cross-sectional	ACLR only	21 (15M/6F)	24.6 ± 9.3	Mean 229.9 days (≥6 M); all cleared RTP LSI >90%	Laboratory
Kember et al. ⁶²	Cross-sectional	Healthy athletes (competitive netball)	12 (12 F)	20.8 ± 2.6	N/A — no ACLR	Laboratory / Court
Calisti et al. ³⁴	Cross-sectional	ACLR/ACLD + Healthy controls	43 (ACLR:10M/11F; CTRL: 10M/12F)	ACLR: 24.2 ± 3.5 CTRL: 26.5 ± 3.2	Mean 3.9 ± 2.5 y post-injury (19 ACLR + 2 ACLD; mixed grafts)	Laboratory
Gokeler et al. ⁶³	Cross-sectional	ACLR + Healthy controls	22 (ACLR: 6M/6F; CTRL: 5M/5F)	ACLR: 27.4 ± 9.6 CTRL: 21.0 ± 0.	Mean 10 ± 2.4 M post-ACLR; hamstring graft; cleared for RTS	Laboratory
Gustavsson et al. ⁵³	Cross-sectional + Test–retest reliability	ACLR + ACL injury + Healthy controls	80 (ACLR: 25M/10F; ACL inj.: 18M/12F; CTRL: 9M/6F)	ACLR: 27 ± 7 ACL inj.: 31 ± 9 CTRL: 28 ± 4	ACLR: ~6 M post-reconstruction ACL inj.: 4–44 M post-injury	Laboratory
Leister et al. ⁶⁴	Cross-sectional (pilot)	Healthy adults	42 (20M/ 22F)	30.4 ± 6.6 (range 18–47)	N/A — no ACLR	Laboratory
Lessi & Serrão. ⁴³	Prospective comparative (Level II)	ACLR + Healthy controls (matched)	40 (ACLR: 13M/7F; CTRL: 13M/7F)	ACLR: 25.1 ± 4.2 CTRL: 23.6 ± 2.9	≥12 M post-ACLR; recreational athletes (≥3 sessions/wk)	Laboratory
van Melick et al. ³⁸	Cross-sectional case-control	ACLR + Healthy controls (all males; recreational soccer)	33 (ACLR: 14M; CTRL: 19M)	ACLR: 23.2 ± 3.6 CTRL: 21.3 ± 3.0	Mean 12.4 ± 3.5 M post-ACLR; LSI >90% confirmed by physio	Grass pitch + Laboratory
Smeets et al. ⁵⁰	Cross-sectional	ACLR + Healthy controls (matched for age, sex, sport)	42 (ACLR: 15M/6F; CTRL: 15M/6F)	ACLR: 23.8 ± 4.2	Mean 258.6 ± 54 days post-op; semitendinosus autograft; cleared for full training	Laboratory
Song et al. ⁶⁵	Cross-sectional	Healthy recreational athletes	34 (17M/17F)	22.5 ± 2.8	N/A — no ACLR; unilateral fatigue applied to one limb	Laboratory
Wesley et al. ²⁷	Cross-sectional	Healthy athletes (varsity/club/intramural sport)	36 (18M/18F)	19.3 ± 1.2	N/A — no ACLR; active ≥3 days/wk; no ACL history	Laboratory
White et al. ⁴⁵	Randomised crossover	Healthy athletes	20 (4M/16F)	23.7 ± 3.0	N/A — no ACLR; no ACL history	Laboratory

ACLR = anterior cruciate ligament reconstruction; ACLD = anterior cruciate ligament deficient; CTRL = control; inj. = injury; LSI = limb symmetry index; RTP = return to play; RTS = return to sport; M = months (Time post-ACLR column) or male (Sex column); F = female; Y = years; wk = week; N/A = not applicable; NR = not reported.

2.4.2 Fatigue Protocol Classification

All twelve studies utilised distinct fatigue induction methods or protocols, implemented either prior to or during the administration of RTS testing. Studies were categorised according to the established central-peripheral fatigue framework, which distinguishes fatigue arising from impaired neural drive (central fatigue) from fatigue arising from impairments within the muscle itself (peripheral fatigue)⁶⁶. Three fatigue induction approaches were identified: (1) isolated joint fatigue protocols, which predominantly targeted peripheral fatigue mechanisms by inducing contractile fatigue in a specific muscle group (e.g., isokinetic quadriceps fatiguing tasks); (2) local neuromuscular fatigue protocols, which combined central and peripheral contributions through repeated, high-intensity lower-limb tasks performed to volitional failure (e.g., repeated hopping); and (3) whole-body sport-specific fatigue protocols, which incorporated a greater central fatigue component alongside systemic peripheral fatigue, reflecting the cognitive, perceptual, and decision-making demands of simulated match-play⁴⁹.

2.4.2.1 Local Neuromuscular Fatigue Protocols

The seven studies that employed a local neuromuscular fatigue approach used repeated lower-limb exercises targeting the quadriceps and surrounding musculature, stimulated via squats, lunges, step-ups and countermovement jumps (CMJ)^{30,34,43,45,53,63,64} (Table 3). Fatigue verification methods varied substantially, with no standardised criterion identified. Although most studies used objective performance-based measurements, such as reductions in CMJ/hop performance. Studies using objective performance measurement thresholds for fatigue verification were considerably varied^{30,34,43,63}. Alternative approaches included volitional exhaustion⁶⁴ or no formal fatigue verification, with fatigue assumed following completion of the exercise protocol^{45,53}.

2.4.2.2 Whole-Body/Sport-Specific Fatigue Protocols

Four studies used whole-body sport-specific protocols, each incorporating multi-directional movement and sustained cardiovascular exertion^{27,38,50,62} (Table 3). Although each study described its fatigue protocol as sport-specific, considerable variability was evident even among protocols targeting the same sporting environments^{38,50}. These studies differed in design, duration, and induction mode. Rate of perceived exertion (RPE) was used to verify fatigue in every study, while objective physiological or biomechanical measures, such as heart rate or lower-limb stiffness, were inconsistently reported^{27,62}.

2.4.2.3 Isolated Joint Protocols

Song et al.⁶⁵ was the only study to use an isolated joint fatigue protocol. Participants maintained 60° knee flexion against 50% of their single-leg 1-repetition maximum knee extension load for five repetitions, with 20-second rest intervals. Fatigue was confirmed retrospectively, as the fatigued limb produced about 50% of the knee work of the non-fatigued limb during all hopping tasks. The protocol duration was 10-15 minutes per limb.

2.4.3 Effects of Fatigue on Hop Performance and Limb Symmetry Index

All the studies reported hop and/or jump performance outcomes in the context of fatigue RTS testing (Table 4). Across these studies, a range of unilateral and bilateral hop tasks were assessed, consistent with those used in standard RTS testing⁶⁷. Most commonly, the single leg hops for distance (SLHD), along with triple, crossover, lateral and medial rotation, as well as vertical and backward hop variants.

2.4.3.1. Absolute performance declines

Fatigue consistently reduced absolute hop performance across all studies, tasks, and fatigue-induction methods (Table 4). Objective declines in performance during RTS testing were also observed across all fatigue domains and induction methods, and in both ACLR and healthy populations. However, two studies indicated that healthy/control participants were more resistant to fatigue effects than ACLR participants, evident either as stable LSI values³⁸ or preserved movement quality⁵⁰ under fatigue, where the ACLR group deteriorated (Table 4). White et al.⁴⁵ further demonstrated that fatigue effects varied by induction protocol even within participants, with a step-down protocol producing greater single-leg hop distance decline and asymmetry than a side-hop protocol (Table 4).

Table 3. Fatigue Protocol Details

Author (Year)	Category	Induction Method	Fatigue Threshold / Intensity	Approx. Duration
Tallard et al. ³⁰	Local neuromuscular	Circuit: 10 BW squats ($\geq 90^\circ$ knee flexion) + 5 SL non-CMJJs from 18-inch box + 2 maximal CMJJs + 20-yard sprint.	CMJ $\leq 70\%$ pre-fatigue max on 2 consecutive trials	Mean ~ 18 min (range 2:20–41:03)
Kember et al. ⁶²	Whole-body sport-specific	Netball SSFP (based on Net-Test): 20 reps of 14 netball-specific movements around court markings (~ 150 m/rep); 4 sets $\times$ 5 reps; W:R ratio 1:2; 3-min rest between sets.	RPE-L $\geq 9/10$ AND RPE-B $\geq 9/10$ (CR10 scale)	~ 50 –60 min
Calisti et al. ³⁴	Local neuromuscular	F1 (initial): 2 $\times$ 10 SL squats (90° , 30 cm box) + 2 $\times$ 10 SL step-ups. F2 (maintenance): 8 SL squats + 8 SL step-ups.	$\geq 20\%$ CMJ drop OR $\geq 10\%$ CMJ drop + CR10 > 5	Per-task maintenance
Gokeler et al. ⁶³	Local neuromuscular	Circuit: 10 double-legged squats to 90° knee flexion + 2 maximal CMJJs.	CMJ $\leq 70\%$ pre-fatigue max on 2 consecutive trials	Until threshold (duration NR)
Gustavsson et al. ⁵³	Local neuromuscular (endurance-based hopping)	Side hop: 30 s continuous lateral hops between two 40 cm lines, hands behind back, maximal reps. Square hop: 30 s continuous hops in/out of a 40 $\times$ 40 cm square. If error rate $> 25\%$, second 30 s trial after 3 min rest.	30 s maximal effort; fatigue assumed through task demand — no criterion threshold	30 s per task (< 5 min total battery)
Leister et al. ⁶⁴	Local neuromuscular	2 min continuous alternating squats and lunges at self-selected pace.	Volitional exhaustion within 2 min fixed window; no objective threshold	2 min fixed
Lessi & Serrão. ⁴³	Local neuromuscular	Pre-fatigue SLHD baseline set (3 attempts). Fatigued sets: 10 squats to 90° + 2 maximal vertical jumps + 20 step-ups onto 31 cm box (assessed limb).	$\geq 20\%$ decline in SLHD from pre-fatigue baseline; Borg CR-10 between sets	Variable — multiple sets; no time limit
van Melick et al. ³⁸	Whole-body sport-specific	1-hour structured soccer field session on grass pitch: speed, stability, coordination exercises + soccer-specific drills.	RPE ≈ 14 –15/20 post-session (Borg 6–20; moderate-hard)	~ 60 min
Smeets et al. ⁵⁰	Whole-body sport-specific	SAFT5: 15 m shuttle incorporating slalom, side-stepping, backward running, jogging/sprinting, agility ladder, CMJJs, scissor jumps. Standardised via tape recording.	RPE-L ~ 15 –16/20; RPE-B ~ 16 –17/20 post-protocol (wide individual variation noted)	~ 5 min per bout (+ inter-task repeats)
Song et al. ⁶⁵	Isolated joint	Each held to exhaustion; 20 s rest between reps. Applied to one predetermined limb only. Additional fatigue rep immediately before each post-fatigue hop trial to maintain state.	50% 1RM isometric hold to exhaustion; $\sim 50\%$ reduction in knee work confirmed across hop tasks	~ 10 –15 min (+ pre-trial bolus before each hop)

Wesley et al. ²⁷	Whole-body sport-specific	20 step-up/step-downs (30 cm box) + plyometric bounding 6 m ×2 + 5 squat jumps + 30 m sprint ×2 + 60 m diagonal cutting + 60 m carioca.	≥5 cm decline in CMJ height from pre-fatigue baseline	Mean ~14 min (mean 6.8 circuit reps)
White et al. ⁴⁵	Local neuromuscular (unilateral)	Protocol A: 30-s side-hop (lateral hops over two tape strips 40 cm apart, single-limb, maximal reps. Protocol B: 2-min lateral step-down) unilateral step-down from 30.5 cm box, heel tap to floor, maximal reps. SLHD tested immediately after each protocol.	NR — no formal criterion; performance change used as outcome proxy	30 s (Protocol A); 2 min (Protocol B)

2.4.3.2 LSI stability despite performance decline

LSI, calculated as a composite of percentage similarity between control and targeted (ACL-injured or non-dominant in healthy populations), was an objective inter-limb performance metric used in a quarter of reviewed studies^{30,38,45,53,64,65}. Despite absolute performance declines (Table 4), LSI remained stable in a range of hopping tasks; single-leg hop distance^{38,64}, lateral/side hop^{30,38}, triple hop³⁰, and cross-over hop³⁰. Where comparisons were made between ACLR and uninjured limbs, both limbs often declined similarly, resulting in unchanged LSI values³⁰. ACLR participants showed post-fatigue LSI declines not present in matched controls across several hop tasks³⁸, and LSI outcomes varied by hop direction within the same participants⁶⁵. Some tasks and populations remained above threshold despite performance decline, while others fell below^{38,65}, and as such, the conventional 90% LSI clearance threshold was not consistently breached.

2.4.3.3. Test sensitivity and battery design

Two studies examined the sensitivity of hop test configurations to detect ACLR-related deficits^{34,53}. Both reported that no single test was sufficient, with multi-task batteries outperforming individual tasks in classification accuracy. The inclusion of a fatigued condition further improved detection accuracy; Calisti et al.³⁴ reported that a battery combining one task performed under fatigue with a different task performed without fatigue (fatigued single-leg hop paired with non-fatigued medial rotation hop) outperformed batteries using either condition alone.

2.4.4 Effects of Fatigue on Landing Biomechanics and Movement Quality

Five studies measured kinematic, kinetic, or EMG outcomes following fatigue^{34,43,50,62,63}, while three used the LESS movement quality screen^{27,38,63}.

2.4.4.1 Kinematic and kinetic changes

Four studies identified post-fatigue kinematic and kinetic alterations^{34,43,50,62} (Table 4). These changes included reduced knee flexion, increased frontal-plane loading, as evidenced by trunk deviation, pelvic drop, and knee abduction moment, and altered lower-limb stiffness^{34,43,50,62}. In group comparisons, ACLR participants exhibited greater biomechanical responses to fatigue than controls. In one instance, the direction of this response differed between groups on the same task, rather than only its magnitude: thorax flexion during a vertical hop with 90° rotation increased in the ACLR group, but decreased in controls, whereas knee abduction moment during a lateral hop increased in the ACLR group with no corresponding change in controls⁵⁰. Both ACLR and control groups exhibited increased EMG amplitude (% peak muscle activation) in several lower-limb muscles (vastus lateralis, biceps femoris, gluteus maximus, and gluteus medius) during landing following fatigue⁴³.

Incorporating a fatigued jump-landing condition improved the accuracy of a kinematic-based statistical model to classify participants as having an ACL injury history versus healthy controls, compared to non-fatigued jump data alone³⁴. When instrumented and observational assessments were applied to the same landing task, force-plate-derived kinetic measures (e.g. leg stiffness) showed significant post-fatigue changes, whereas a visually scored, non-instrumented movement quality tool did not⁶².

2.4.4.2 Landing Error Scoring System score changes

All three studies using the LESS reported significant post-fatigue deterioration in movement quality^{27,38,63}. ACLR participants demonstrated larger increases in LESS score compared to controls, with a greater proportion exceeding the clinical risk threshold post-fatigue. ACLR participants demonstrated significantly larger post-fatigue increases in LESS score than controls (ACLR: 3.6 ± 1.5 to 6.8 ± 1.4 ; CTRL: 3.7 ± 1.8 to 4.3 ± 1.7 ; group*time), with a greater proportion of ACLR participants exceeding the ≥ 6 clinical risk threshold post-fatigue (86% vs. 32% in controls)³⁸.

In healthy populations, fatigue also produced meaningful LESS deterioration, with a notable proportion of participants transitioning from low- to high-risk categories following exercise²⁷. Sex differences in LESS scores were observed at both time points, though the fatigue*sex interaction was not significant²⁷. Error frequency analysis identified consistent post-fatigue increases across multiple movement quality items in ACLR participants relative to controls⁶³.

2.4.5 Clinical Feasibility

Local neuromuscular fatigue protocols were generally the most clinically accessible, requiring minimal equipment and modest time demands (Table 5). Feasibility within this category depended on the verification method. Protocols using CMJ measurement required additional equipment^{30,34,63}, whereas this was not required for time-fixed or volitional exhaustion approaches^{53,64}. Whole-body sport-specific fatigue protocols showed greater variability in clinical accessibility, from short multi-directional circuits suitable for a well-equipped gym or sports clinic²⁷, to extended sport-specific sessions that required dedicated courts or pitches and were impractical for standard appointment slots^{38,50}. Isolated joint protocols were limited to specialist laboratory settings due to equipment requirements.

Table 4. Biomechanics and limb symmetry index reported outcomes

Author (Year)	RTS Tests Used	Key Performance Finding (post-fatigue)	LSI post-fatigue (key values)	Primary Statistical Result
Tallard et al. ³⁰	Single, triple, crossover, lateral/medial rotation hop, 6 m timed hop, vertical jump (all unilateral)	Control limb declined post-fatigue: triple hop (-37 ± 17 cm), crossover hop (-41 ± 16 cm), lateral rotation hop (-8 ± 3 cm). ACLR limb lower than control at baseline (-15 ± 3 cm) but not post-fatigue.	Composite LSI stable post-fatigue despite bilateral decline; control limb fell as much as ACLR limb on several tasks.	Triple hop: $p=0.045$, $ES=0.28$. Crossover: $p=0.016$, $ES=0.34$. Lateral rot.: $p=0.009$, $ES=0.21$. Baseline single hop: $p=0.0002$, $ES=0.40$
Kember et al. ⁶²	Tuck jump assessment (TJA) — bilateral, 10 s	Jump height $\downarrow$ ($0.24\rightarrow 0.21$ m, $g=0.63$); flight time $\downarrow$ ($0.44\rightarrow 0.41$ s, $g=0.68$); peak COM displacement $\downarrow$ ($0.16\rightarrow 0.14$ m, $g=0.69$); kleg $\uparrow$ ($25.79\rightarrow 29.41$ BW·m ⁻¹ , $g=0.45$). TJA composite score: no significant change ($11\pm 3\rightarrow 11\pm 2$, $p=.93$).	NR	kleg: $p=.005$, $g=0.45$. COM displacement: $p<.001$, $g=0.69$. Jump height: $p=.003$, $g=0.63$. Flight time: $p=.005$, $g=0.68$. TJA composite: $p=.93$ (NS)
Calisti et al. ³⁴	SLH, uCMJ, MRH, COH — fatigued and non-fatigued conditions	No single task consistently outperformed others. Fatigued condition improved classification accuracy across most tasks. Best battery: fatigued SLH + non-fatigued MRH.	NR	Fatigued SLH classification rate 93.0% (Nagelkerke R^2 up to 0.832) vs. non-fatigued MRH 90.7%
Gokeler et al. ⁶³	Drop jump + LESS	LESS error frequencies higher in ACLR post-fatigue: knee flexion at IC (90% vs 30%), asymmetrical foot contact (60% vs 10%), hip extension (60% vs 20%), lateral trunk flexion (50% vs 0%).	NR	Descriptive only — no inferential statistics
Gustavsson et al. ⁵³	Vertical jump, hop for distance, drop double hop, square hop, side hop (all unilateral)	Only 1/10 patients achieved normal hop performance at 6 mo post-ACLR. Side hop highest individual sensitivity for ACLR deficits. Endurance hops exposed deficits missed by single maximal-effort tests.	Used as classification threshold only (no pre/post change value)	Side hop sensitivity: 69%; Vertical jump: 86%; Battery: 91% (ACLR); Specificity: 67–100%
Leister et al. ⁶⁴	SLHD, triple crossover hop, 6 m timed hop, side hop (all unilateral)	Mean SLHD declined 10.5 cm post-fatigue ($138.8\rightarrow 128.3$ cm). Dominant limb > non-dominant at baseline. No sex effect on LSI.	LSI $98.8\pm 4.6\%$ — stable post-fatigue despite 10.5 cm bilateral SLHD decline	SLHD change $p<0.001$ (95% CI: 5.6–15.4 cm); LSI fatigue effect: $p=0$.
Lessi & Serrão. ⁴³	SLHD (fatigue threshold only); drop vertical jump (primary outcome)	SLHD used as fatigue criterion only. No performance or LSI outcomes reported; primary outcomes were kinematic and EMG.	NR	Peak trunk flexion increased significantly post-fatigue ($p<0.01$); Peak knee flexion decreased ($p=0.01$); Peak contralateral pelvic drop increased ($p=0.01$); All EMG differences statistically significant ($p\leq 0.02$).

van Melick et al. ³⁸	Hop for distance, vertical jump, side hop (unilateral); CMJ + LESS (bilateral)	ACLR: significant post-fatigue declines in hop for distance and side hop not seen in controls. Authors recommend raising RTS LSI threshold to ≥95% (not 90%) following ACLR rehabilitation.	ACLR hop for distance and side hop LSI declined post-fatigue; CTRL stable. Group*time significant for both.	Hop for distance: group*time p=0.042; Side hop: group*time p=0.022; LESS group*time: p<0.001
Smeets et al. ⁵⁰	SLH for distance, medial/lateral hop, vertical hop 90° rotation (all unilateral)	Performance declined in both groups post-fatigue (SLH: ACLR 1.87→1.79 m; CTRL 1.87→1.77 m; p<0.001). Vertical hop 90°L: ACLR ↓ p=0.003. Only ACLR group showed biomechanical deterioration on interaction effects.	NR	SLH fatigue effect: p<0.001; Vertical hop 90°L: p=0.003; Knee abd. moment (lateral hop): p=0.044, ES=0.57; Thorax flexion (vertical hop 90°): p<0.001, ES=0.55
Song et al. ⁶⁵	Forward, vertical, backward hop — all unilateral (fatigued vs non-fatigued limb)	All three hop LSIs declined post-fatigue. Backward hop largest decline (~15%); forward hop smallest (~8%). Knee work ↓ ~45–57% in fatigued limb. Hip and ankle contributions preserved forward hop LSI above 90% threshold.	Forward: 1.01→0.93 (~8%); Vertical: 1.01→0.90 (~11%); Backward: 0.99→0.84 (~15%)	All LSI changes: p<0.001; Backward vs forward LSI: p<0.001; Knee work forward: ↑57%, p<0.001
Wesley et al. ²⁷	Drop jump + LESS (bilateral); vertical jump height	LESS scores increased post-fatigue in both sexes. 4 males and 7 females transitioned from low- to high-risk LESS category. Females scored higher than males at both time points. Vertical jump declined in both sexes (males: 50.4→42.3 cm; females: 42.8→37.2 cm; both p<0.001).	NR	LESS: pre-5.0±2.0 → post 6.3±2.0 (+1.3, 95% CI 0.8–1.8), p<0.001; Sex main effect: p=0.04; Sex*time: p=0.62 (NS)
White et al. ⁴⁵	Single-leg forward hop (both limbs; randomised crossover, 2 protocols)	Step-down (Protocol B) produced greater SLHD decline than side-hop (Protocol A). 40% of step-down vs 15% of side-hop trials exceeded MDC (13 cm). Dominant > non-dominant on both protocols.	Step-down: larger LSI asymmetry than side-hop. Dominant > non-dominant: p<0.05 (both protocols).	Step-down: Δ=-12.3 cm, d=-0.46; Side-hop: Δ=-8.0 cm, d=-0.33; Dominant > non-dominant: p<0.05

ACLR = anterior cruciate ligament reconstruction; CTRL = control; LSI = limb symmetry index; RTS = return to sport; SLHD = single-leg hop for distance; LESS = Landing Error Scoring System; CMJ = countermovement jump; SLH = single-leg hop; uCMJ = unilateral CMJ; MRH = medial rotation hop; COH = crossover hop; COM = centre of mass; MDC = minimal detectable change; IC = initial contact; NR = not reported.

Table 5. Clinical Feasibility Summary

Author (Year)	Protocol Category	Equipment Required	Estimated Time	Setting Suitability	Ecological Validity	Feasibility Rating
Tallard et al. ³⁰	Local neuromuscular (CMJ threshold)	Plyometric box (18-inch); Vertec jump measurement system or equivalent (contact mat / smartphone CMJ app); clear floor space	Mean ~18 min (range 2–41 min)	MODERATE — gym, sports clinic, or outpatient physio with jump-measurement tool. Smartphone CMJ apps reduce equipment barrier.	Low-moderate	★★★★☆ MODERATE
Kember et al. ⁶²	Whole-body sport-specific (extended sport session)	Netball court (~30 m); cones, bibs, balls; timing gates; 50–60 min session. High space and organisation demand.	~50–60 min	LOW for clinical use — requires dedicated court, sport equipment, and extended session. Best suited to high-performance sport environments.	Very high (full sport session)	★★☆☆☆ LOW (clinical use)
Calisti et al. ³⁴	Local neuromuscular (CMJ threshold + maintenance)	30 cm box/step; force plate or contact mat for CMJ verification; CR10 scale (printed/digital). Floor space for jump tasks.	Per-task maintenance throughout session (~40–60 min total session)	MODERATE — requires jump-measurement tool for CMJ verification. Maintenance sets between tasks extend overall session duration. Suitable for sports clinic or gym.	Low-moderate	★★★★☆ MODERATE
Gokeler et al. ⁶³	Local neuromuscular (CMJ threshold)	Open floor space; CMJ measurement tool (contact mat or equivalent). Post-fatigue LESS requires video camera for 2D analysis.	Until threshold (duration NR; likely 15–30 min)	MODERATE — requires CMJ measurement and video recording for LESS. Suitable for sports clinic or gym with basic equipment.	Low-moderate	★★★★☆ MODERATE
Gustavsson et al. ⁵³	Local neuromuscular (endurance-based hopping)	Tape to mark 40 cm lines / 40×40 cm square on floor. No other equipment needed.	30 s per task; <5 min for full hop battery	HIGH — requires only marked floor space. Suitable for any clinical, gym, or outpatient setting.	Low-moderate	★★★★★ HIGH
Leister et al. ⁶⁴	Local neuromuscular (time-fixed / volitional)	Floor space only — no equipment required. No measurement tools needed.	2 min fixed	HIGH — suitable for any outpatient physiotherapy, gym, or sports clinic. Minimal supervision.	Low-moderate	★★★★★ HIGH

Lessi & Serrão. ⁴³	Local neuromuscular (hop distance threshold)	31 cm step/box; measuring tape or marked floor for hop distance measurement; floor space ~10 m.	Variable — multiple sets; typically, 20–40 min	MODERATE-HIGH — requires space for hop measurement but no specialist equipment. Suitable for sports clinic or gym with clear floor area.	Low-moderate	★★★★☆ MODERATE
van Melick et al. ³⁸	Whole-body sport-specific (extended sport session)	Grass soccer pitch; balls, cones, bibs; ~60 min session. Requires outdoor or large indoor sports space.	~60 min	LOW for standard clinical use — requires grass pitch and extended session. More feasible in sports club or high-performance settings.	Very high (full sport session on pitch)	★★★☆☆ LOW (clinical use)
Smeets et al. ⁵⁰	Whole-body sport-specific (shuttle protocol; SAFT5)	15 m corridor or court; agility ladder; cones; tape-recorded instructions. No specialist equipment.	~5 min per bout (+ inter-task repeats throughout session)	MODERATE — requires 15 m clear corridor or court. Standardised (tape-recorded), reproducible. More feasible than full sport sessions.	High (multi-directional sport-replicating)	★★★★☆ MODERATE
Song et al. ⁶⁵	Local neuromuscular (isolated quadriceps)	Isokinetic dynamometer or load cell for 1RM testing; force plate + 3D motion capture for fatigue verification. High-cost specialist equipment required.	~10–15 min (+ pre-trial bolus before each hop)	LOW — specialist laboratory or sports science centre only. Isokinetic/force plate equipment not available in standard outpatient or community settings.	Low (isolated joint; not sport-replicating)	★★☆☆☆ LOW (specialist only)
Wesley et al. ²⁷	Whole-body sport-specific (short circuit ≤15 min)	30 cm plyometric box; open floor space ≥30 m for sprint and cutting lanes; HR monitor recommended. No specialist equipment.	Mean ~14 min (mean 6.8 circuit reps)	MODERATE — requires large open floor space (sprint + cutting lanes). Suitable for well-equipped gym, sports hall, or sports clinic with adequate space. Not typical outpatient.	High (multi-directional sport-replicating)	★★★★☆ MODERATE
White et al. ⁴⁵	Local neuromuscular (time-fixed / unilateral)	Standard clinical step (30.5 cm) for step-down protocol; tape strips for side-hop. No other equipment needed.	30 s (Protocol A) 2 min (Protocol B)	HIGH — suitable for any outpatient physiotherapy, gym, or sports clinic. Protocol B (step-down) requires only a standard clinical step. Minimal supervision.	Low-moderate	★★★★★ HIGH

Rating scale (for typical outpatient/sports clinic settings): h ★★★★★ High ★★★★★ Moderate ★☆☆☆☆ Low. CMJ = countermovement jump; LESS = Landing Error Scoring System; SAFT5 = Soccer-specific Aerobic Field Test; 1RM = one-repetition maximum; HR = heart rate; NR = not reported / not applicable.

2.5 Discussion

This review aimed to outline fatigue protocols used alongside ACL RTS assessments, evaluate their clinical relevance, and highlight gaps to inform future research and clinical practice. Across the reviewed studies, fatigue consistently altered functional performance, movement quality, and biomechanical outcomes compared with rested assessments. Although the magnitude and nature of reported changes varied, the overall evidence indicates that fatigue reveals deficits not apparent during rested RTS assessments. This finding supports incorporating fatigue protocols within RTS evaluations, especially considering the ongoing limitations of conventionally rested testing in predicting a safe return⁶⁷. Interpretation is limited by substantial methodological heterogeneity across the evidence base. Studies varied across participant populations, fatigue induction methods/verification criteria and RTS testing batteries, making direct comparison challenging and preventing the identification of an optimal fatigue protocol. This heterogeneity reflects the developmental stage of this research area, rather than undermining fatigue testing's value. The available evidence consistently supports the importance of assessing individuals under fatigued conditions; however, no standardised protocol has yet demonstrated clinical feasibility, reliability, and ecological validity. Establishing such a protocol would represent a critical step toward integrating fatigue assessment into routine RTS decision-making.

Almost half of the reviewed studies recruited healthy athletic populations^{27,45,62,64,65}. Healthy populations provide a normative reference for interpreting fatigue-related changes following ACLR. Understanding fatigue effects in uninjured individuals allows clearer contextualisation of ACLR-specific findings and helps distinguish injury-related deficits from general fatigue/fatigue protocol effects. Healthy cohorts function as essential comparators within the evidence base. This approach is particularly characteristic of foundational research aimed at developing novel RTS testing batteries, in which normative data precede the investigation of clinically meaningful thresholds in the context of the ACL^{68,69}. Mechanistically, use of healthy participants aligns with research aimed at isolating the effect of fatigue itself on landing kinetics and kinematics, independent of any confounding influence from ACL injury, reconstruction, or even the rehabilitation process. By establishing how fatigue alters landing mechanics in an uninjured population, these studies provide a baseline for attributing ACLR-specific findings to injury or surgical management, rather than fatigue itself⁷⁰. Where ACLR populations were studied, there were often differences in graft type, time since surgery, rehabilitation progression, and prior sport participation or competitive level that were inconsistently reported^{30,34,38,43,50,53,69,71,72}. This variability limits group-level comparisons but reflects diversity in clinical practice. Current RTS decision-making frameworks are not typically stratified by graft type or

surgical approaches, consistent with clinical application^{14,73}. Future research could assess how clinical and surgical factors potentially moderate fatigue responses during RTS testing.

Fatigue protocols in the reviewed literature produced both subtle, yet significant, changes in RTS performance and movement quality. There was substantial variability in how fatigue was defined, induced, and verified. Protocol durations ranged from 30 seconds^{45,53} to 60 minutes^{38,62}. Criteria for confirming fatigue included reductions in CMJ performance³⁰, RPE^{38,50,62}, or in some cases, no explicit verification^{45,53,64}. Thus, fatigue was operationalised across a broad range of physiological and perceptual states rather than as a single construct, which constrains direct comparison of findings. Differences in protocol design likely reflect differences in neuromuscular and metabolic states at RTS testing. Between-study variation may result from both participant response and the fatigue stimulus. Cross-study comparisons should be viewed as comparisons across related, but non-equivalent fatigue constructs, rather than a single standardised intervention.

The different fatigue protocols could be grouped into three domains based on physiological emphasis: localised neuromuscular, whole-body sport-specific, and isolated joint fatigue⁴⁹. Each domain targets different components of the fatigue continuum. For example, a short-duration squat protocol and a prolonged sport simulation both induce fatigue, but likely produce distinct central and peripheral fatigue profiles and different performance responses during RTS testing⁴⁴. White et al.⁴⁵ reported that different fatigue protocols within the same cohort produced divergent effect sizes, indicating the sensitivity of RTS outcomes to the fatigue stimulus. The differences in protocol design also reflect a tension between ecological validity and clinical feasibility. Whole-body sport-specific protocols replicate sport demands but are resource-intensive and difficult to standardise. While localised neuromuscular protocols may be more practical and reproducible, they may not represent sport-relevant fatigue states. Isolated joint protocols form a laboratory-based subset within this category, generally using isokinetic dynamometry to induce and measure fatigue. Among these, only Song et al.⁶⁵ combined an isokinetic fatigue protocol with a formal RTS test. In contrast, DiFabio et al.⁷² and Bagley et al.⁷¹ used similar isokinetic fatigue methods but did not include formal RTS assessment, serving instead as mechanistic comparators. Despite this, a time-restricted localised neuromuscular protocol with defined fatigue verification criteria and minimal equipment demands might be the most pragmatic candidate for clinical translation, particularly where delivery within a standard clinical appointment is a prerequisite for routine implementation. No protocol has been validated across both domains and ACLR populations, so protocol selection remains context dependent. Furthermore, no study has evaluated a fatigue protocol in relation to a validated and standardised RTS testing battery. Without this comparison, fatigue-induced changes are only related

to explicit individual RTS tasks, potentially barring interpretation that could otherwise be generated across a multi-planar movement battery that would be more ecologically valid in a sporting context⁴⁴.

There was variability in the task selection, sequencing, and outcome prioritisation for the RTS testing batteries. Common assessments included hop tests, jump performance measures, and movement quality screens, but implementation was inconsistent. Heterogeneity exists at both the fatigue stimulus and outcome assessment levels, limiting the precision of stimulus-response relationships and constraining unified causal inferences. Future research should align fatigue-induction methods and RTS assessment batteries within defined conceptual frameworks. Furthermore, given that kinematic responses to fatigue in healthy populations remain incompletely characterised, establishing normative movement data under defined fatigue conditions represents a necessary methodological precursor to interpreting fatigue-induced deficits in ACLR cohorts.

Fatigue alters athlete performance during RTS assessment in ways not observed under rested conditions. Three studies reported reduced performance metrics, independent of group allocation or ACL status^{64,50,30}, indicating that fatigue can reveal deficits not detected by standardised, non-fatigued assessments. However, interpreting fatigued performance for RTS clearance remains challenging. Existing outcome measures were not designed for fatigued testing, and their response under fatigue may not correspond to the functional capacities of interest. Although absolute performance typically declines after fatigue, LSI may remain unchanged if both limbs are similarly affected^{30,64}. This questions the validity of LSI as an indicator of injured limb recovery. Compensatory movement strategies further complicate interpretation. Under fatigue, athletes may modify motor patterns to maintain task performance, which can obscure deficits in neuromuscular control and movement quality^{39,74}. Performance metrics may suggest readiness despite underlying changes in movement strategy not captured by symmetry- or outcome-based measures. LSI quantifies inter-limb performance but does not assess absolute capacity or movement quality under physiological stress.

These findings indicate that fatigue reveals performance characteristics not identified by standard RTS testing batteries. Fatigued conditions are more likely to elicit ACLR-specific changes in movement strategy and performance control that are not evident during rested assessments or captured by common clinical metrics. RTS assessment batteries should incorporate measures sensitive to fatigue-induced changes in both performance capacity and movement quality to better reflect sporting demands.

Fatigue alters landing biomechanics, but these changes are heterogeneous and reflect distinct adaptation strategies rather than a uniform deterioration. Observed responses include reduced joint excursion and increased frontal-plane instability, including valgus loading and trunk deviation^{43,50}. These adaptations likely result from differences in energy absorption demands and neuromuscular control. The specific fatigue protocol influences the biomechanical response: local neuromuscular fatigue is associated with reduced joint excursion and increased stiffness⁶², whereas whole-body or sport-specific protocols more often produce multi-segmental control deficits³⁸. As these protocols engage different physiological systems, their biomechanical effects represent distinct fatigue states rather than directly comparable presentations.

ACLR and healthy populations exhibit distinct responses to fatigue. Individuals with ACLR show greater frontal-plane perturbations and reduced adaptability in movement strategies under fatigue^{50,69}, whereas healthy individuals are more able to reorganise movement patterns to maintain stability. This suggests that fatigue reduces the capacity to compensate for existing neuromuscular deficits rather than introducing new impairments. These biomechanical alterations are not consistently detected by clinical assessment tools. While kinetic and kinematic analyses reveal changes in loading and movement strategies under fatigue, observational and performance-based measures often fail to detect these differences^{50,62}, highlighting a disconnect between movement quality and commonly used outcome assessments.

Biomechanical responses to fatigue are influenced by both the fatigue-induction protocol⁴⁵ and population characteristics, including ACLR history^{38,50}. Fatigue does not uniformly degrade movement quality but instead shifts the balance among energy absorption, joint control, and compensatory strategies. Evidence includes changes in leg stiffness and centre-of-mass control⁶², joint-specific deterioration in the ACLR group⁵⁰, and increased muscle recruitment, indicating compensatory neuromuscular responses⁴³. This heterogeneity limits the ability to draw clinically meaningful conclusions and underscores the need for standardised fatigue protocols to improve comparability in RTS research.

2.5.1 Clinical Implications of Fatigue in ACL RTS Testing

Current RTS readiness assessments rely on non-fatigued conditions, which may not reflect the functional capacity required for sport. Fatigue-related changes suggest that individuals meeting RTS criteria at rest may show reduced performance or altered movement control when fatigued, indicating a gap in the ecological validity of current testing approaches³⁸. Clinicians should interpret RTS outcomes in context, and current RTS clearance may be better considered a conditional indicator of readiness to return to activity under specific testing constraints or without fatigue-

induced application. Incorporating fatigue into RTS assessment, whether through pre-fatiguing protocols, integrating fatigue into test batteries, or assessing later in a testing session, may reveal performance deficits not captured under rested conditions. This approach is intended to complement, not replace, existing RTS frameworks.

These findings have implications for reinjury risk. If fatigue exposes deficits in athletes who otherwise meet RTS criteria, this may partly explain injuries or reinjuries occurring under the physical demands of competition. Rehabilitation and RTS preparation should therefore emphasise the ability to maintain neuromuscular control and functional performance under fatigue. There is currently no consensus on a fatigue protocol suitable for routine clinical implementation. This limits translation into practice and highlights the need to develop practical, standardised, and reproducible fatigue-based RTS assessment approaches that better reflect sport demands.

2.5.2 Limitations

Several methodological limitations are noted. This review included only studies that examined fatigue within clinic-based RTS testing. Studies focused solely on mechanistic or methodological validation were excluded, which may have limited the scope of evidence. Study screening and selection were conducted by the lead author, with confirmation by a second author. A third reviewer was available for dispute resolution but was not required. This process did not follow the independent dual screening recommended by JBI guidance, and selection bias cannot be excluded. Inter-rater agreement was not evaluated. In line with the Arksey and O'Malley framework, no formal appraisal of methodological quality or risk of bias was performed. Studies were mapped rather than weighted by methodological rigour, so findings are descriptive and exploratory. No established framework exists for evaluating the clinical feasibility of fatigue protocols. This review developed a structured feasibility rating system based on evidence synthesis. The framework has not been empirically developed or evaluated for inter-rater reliability or external validity.

2.6 Conclusion

This scoping review synthesised current evidence on fatigue protocols applied during RTS testing after ACLR. Fatigue consistently altered hop performance, landing biomechanics, and movement quality, but these effects were not consistently identified by standard clinical RTS measures. LSI was particularly prone to misinterpretation under fatigue, as bilateral reductions in performance often concealed ongoing neuromuscular deficits in the reconstructed limb. Individuals with ACLR showed greater frontal-plane deviations and reduced adaptability under physiological stress compared to

healthy controls. These findings indicate that fatigue reveals pre-existing neuromuscular deficits by limiting compensatory mechanisms, rather than introducing new impairments.

Considerable methodological heterogeneity in fatigue protocols, outcome measures, and participant characteristics limited comparability and prevented causal inference. No study assessed a fatigue protocol within an established RTS test battery, and no protocol has been validated for routine clinical use in ACLR populations. Future research should focus on developing and validating a standardised, clinically applicable fatigue protocol for integration into existing RTS frameworks. Incorporating validated fatigue protocols into multidimensional RTS assessments within defined conceptual frameworks may improve detection of residual neuromuscular deficits and inform RTS decisions.

Prelude to Chapter 3

This chapter moves from evidence mapping to the development and implementation of a fatigue protocol, addressing the lack of protocols tested against a standardised ACL RTS battery identified in the previous scoping review. A clinically feasible fatigue protocol is paired with a standardised RTS test battery in a healthy population. The study also provides the first descriptive analysis of force-time kinetic variables associated with ACL injury mechanisms that are not currently included in standard RTS outcomes. By assessing the effects of fatigue on both standardised RTS outcomes and phase-specific kinetic variables within the same cohort, this study offers preliminary data on whether fatigue influences standard RTS outcomes and whether force-time mechanics demonstrate a distinct pattern of change that warrants further investigation.

Chapter 3: The Impact of Fatigue on Test Outcomes in ACL Return-To-Sport Assessment

3.1 Abstract

Background: Return-to-sport (RTS) testing after anterior cruciate ligament injury is typically performed in a rested state, despite fatigue being intrinsic to sport. Conventional RTS metrics (hop distance, jump height, limb symmetry) may fail to detect deficits that emerge under fatigue, risking overestimation of readiness. This is particularly relevant for female athletes, who sustain non-contact ACL injuries 3-6 times more often than males and show and show higher-risk landing mechanics that fatigue may further compromise. This study examined the acute effects of fatigue on kinetic outcomes during RTS testing in female athletes.

Methods: Fifteen female athletes (23.1 ± 4.7 years) completed baseline and fatigued sessions, separated by at least 72 hours. Fatigue was induced until countermovement jump (CMJ) height decreased by at least 30%. Participants completed an RTS battery (CMJ, single-leg vertical jump, single-leg hop for distance, single-leg drop jump, isometric quadriceps and hamstring strength). Eleven primary outcomes were tested via paired t-tests (Holm-corrected); 47 kinetic variables were analysed descriptively.

Results: Fatigue was confirmed (heart rate 187.9 bpm; RPE 15–20). Eccentric peak force and braking impulse declined 7–9% during the drop jump ($d_z = 0.64$ – 0.96), and landing rate of force development declined 9–10% during the CMJ ($d_z = 0.88$ – 0.98). Only quadriceps strength (-9.8% , $p < .001$) and hop distance (-17.3% , $p = .041$) declined significantly; remaining outcomes were largely unaffected.

Conclusions: Fatigue produced consistent impairment in kinetic variables, particularly eccentric force absorption and landing force regulation, not detected by conventional RTS metrics. Female athletes may show preserved performance despite underlying deficits, likely relevant given their elevated ACL injury risk. Kinetic assessment should be considered alongside conventional metrics when evaluating RTS readiness under fatigue.

3.2 Introduction

Return-to-sport (RTS) testing represents a critical decision point in athletic rehabilitation, intended to determine whether an athlete possesses sufficient physical, biomechanical, and psychological readiness to safely resume sport participation. Rather than signifying a terminal endpoint of rehabilitation, RTS clearance marks the point from which progressive re-exposure to training and competition can begin^{75,76}. In theory, RTS decisions depend on contextual factors beyond assessment outcomes, including sport-specific demands, cumulative fatigue, and variability in competitive environments⁷⁶. Similarly, psychological readiness and confidence in the reconstructed knee have been found to further influence RTS success and reinjury risk⁷⁷, factors often poorly emphasised in RTS decision making¹⁴. While RTS protocols should replicate environmental/sporting demands to validate clinical decisions, current practices may often fall short. Anterior cruciate ligament reconstruction (ACLR) provides a particularly relevant example of the RTS challenge. Despite the widespread use of RTS testing following ACLR, outcomes remain disappointing. Reinjury rates approach 30% in athletic populations and are even higher in young athletes participating in multidirectional sports^{21,22}. Furthermore, only about half of athletes regain their pre-injury performance level following reconstruction^{14,35}. These unsatisfactory outcomes persist despite many athletes successfully meeting established RTS criteria prior to clearance. The apparent gap between passing an RTS assessment and being genuinely prepared for the demands of competitive sport is not trivial, raising an important question: do current RTS assessments adequately capture the neuromuscular deficits most relevant to successful and sustainable return to sport?

Most contemporary RTS batteries determine readiness using performance-based outcome measures such as hop distance, jump height, strength, and limb symmetry indices (LSI)¹⁴. Performance metrics, whilst intuitive, primarily capture RTS information at a binary level (pass/fail), without consideration of the mechanics behind task completion. Consequently, athletes may restore apparent task performance while continuing to rely on compensatory movement strategies that mask persistent neuromuscular deficits³³. Recognition of this limitation has led to the inclusion of movement-quality assessments such as the Landing Error Scoring System²⁷. However, these assessments remain largely observational, identifying visible movement errors rather than objectively quantifying the underlying control of force throughout the lower limb.

A substantial body of biomechanical literature has identified movement characteristics associated with increased ACL loading and injury risk, including altered hip and knee joint moments, reduced capacity to attenuate landing forces, impaired whole-body balance, and altered trunk positioning during landing and cutting manoeuvres^{3,78–80}. These movement characteristics influence how

external loads are generated, absorbed, and distributed throughout the lower extremity during high-demand sporting tasks. Importantly, many of these neuromuscular deficits persist following ACL reconstruction despite completion of rehabilitation and achievement of conventional RTS criteria^{18,49}. Indeed, kinematic and kinetic asymmetries remain detectable during functional hop tasks despite restoration of hop performance⁸¹, indicating that performance outcomes alone likely cannot fully characterise knee function after reconstruction.

Force-time-derived kinetic variables enable some of the quantification of movement strategies. However, rather than simply determining whether a task is completed successfully, kinetic measures begin to characterise how force is generated, may be absorbed, and transferred throughout movement⁸¹. Kotsifaki et al.⁸¹ demonstrated that professional athletes more than nine months post-ACLR achieved satisfactory hop performance but continued to exhibit deficits in concentric impulse, eccentric deceleration impulse, and eccentric rate of force development (RFD). Likewise, early-phase RFD often remains impaired despite restoration of maximal strength and has been associated with unsuccessful RTS outcomes and increased risk of subsequent ACL injury^{36,82}. Collectively, these findings suggest that restoration of performance does not necessarily represent restoration of neuromuscular function, highlighting the potential value of kinetic assessment within RTS decision-making.

An equally important limitation is that ACL RTS testing is almost universally performed under rested conditions. Represented as a transient exercise-induced reduction in a muscle's capacity to generate force or power⁸³, fatigue is not incidental to sport; it is inherent to it. Fatigue alters movement characteristics linked to ACL injury risk, including reduced hip and knee flexion, diminished eccentric braking capacity, increased dynamic knee valgus, and greater inter-limb asymmetry^{40,41}. Critically, these deficits may remain concealed during rested state conventional testing. Van Melick et al.³⁸ demonstrated that movement quality deteriorated more following fatigue in individuals after ACLR compared with healthy controls despite similar task performance, while Tallard et al.³⁰ reported that fatigue exposed asymmetries not evident during rested assessment. If the neuromuscular deficits most relevant to ACL reinjury emerge more prominently under accumulated physiological fatigue, then conventional RTS testing may systematically overestimate an athlete's readiness status.

Despite growing evidence that fatigue influences movement quality, its effects on force-time characteristics during RTS assessment remain largely unknown. Little is known about how fatigue influences kinetic variables such as RFD, impulse, and landing force, or how these changes affect interpretation of symmetry-based RTS outcomes. Establishing normative responses under fatigued

conditions is therefore a necessary step before fatigue-based kinetic assessment can be meaningfully translated to clinical ACLR populations.

This question may be particularly relevant in female athletes, who sustain non-contact ACL injuries at approximately three-six times the rate of males⁴⁸. Females also demonstrate neuromuscular characteristics associated with elevated injury risk, including greater dynamic knee valgus, altered landing mechanics, and differences in lower-limb control strategies^{48,84}. These neuromuscular characteristics influence how forces are generated, absorbed, and distributed throughout the lower extremity during landing and change-of-direction tasks, manoeuvres frequently implicated in ACL injury mechanisms^{34,50}. Fatigue is associated with deterioration in landing mechanics in both sexes, and there is no consistent evidence that females are affected to a greater degree than males following exercise-based fatigue protocols^{27,40}. Fatigue may therefore further compromise neuromuscular regulation of force during high-demand sporting tasks in a population that already exhibits biomechanical differences. Consequently, female athletes provide an appropriate population in which to establish normative fatigue-related changes in lower-limb kinetics.

Accordingly, this study investigated the acute effects of a standardised neuromuscular fatigue protocol on lower-limb kinetics during a standardised RTS assessment battery in healthy recreational female athletes. By establishing responses in clinically relevant outcome variables under rested and fatigued conditions, this study provides a methodological foundation for future fatigue-based kinetic assessment within clinical ACLR RTS decision-making.

3.3 Methods

3.3.1 Study Design

The study employs a within-subjects repeated-measures design to evaluate the acute effects of a standardised neuromuscular fatigue protocol on lower-limb kinetics and RTS performance outcomes during RTS assessment tasks within a healthy population. Ethical approval for this study was granted by the Auckland University of Technology Ethics Committee (#25/248). Written informed consent was obtained from all participants prior to data collection. Each participant completed two testing sessions: baseline (i.e. non-fatigued) and fatigued. The sessions were separated by a minimum of 72 hours to ensure full recovery between conditions. Participants were also asked to refrain from other forms of exercise within this time frame. The order of testing conditions was standardised, so baseline testing always preceded the fatigue session. Within each session, the order of tests was randomised to control for learning effects across the RTS kinetic testing battery.

3.3.2 Study Participants

Fifteen recreationally active female athletes were recruited via convenience sampling from community and club-level sport. Eligibility criteria required participants to be aged between 18 and 35 years and to have engaged in regularly organised field or court-based sport. Participation was restricted to those competing in organised teams at community or club level, excluding elite, national, and professional athletes. A healthy cohort was deliberately chosen over athletes with a history of ACL injury or reconstruction, or those currently in rehabilitation. Such athletes introduce confounding variables, including graft type, surgical timing, rehabilitation stage, and pre-existing inter-limb asymmetries. Recruiting healthy athletes allowed these variables to be controlled, so that the effects of fatigue on RTS outcomes could be isolated. Full inclusion/exclusion criteria are presented in Table 6.

Table 6. Participant eligibility criteria

Criteria type	Details
Inclusion criteria	Aged between 18 and 35 years Recreationally active female athletes Regularly engaged in organised field- or court-based sport Competing in organised teams at community or club level
Exclusion criteria	Any lower-limb injury within the six months preceding data collection Any prior history of ACL injury or reconstruction Currently pregnant Any medical condition of a cardiovascular, neurological, or metabolic nature that would contraindicate high-intensity physical activity Competing at elite, national, or professional level

Note. ACL = anterior cruciate ligament. Eligibility was assessed at screening prior to enrolment.

3.3.3 Instrumentation

Kinetic data for the RTS assessment battery were collected from a dual force-plate instrumented treadmill (Bertec, Columbus, OH, USA; 1000 Hz) via Vicon Nexus software (v2.19, Vicon Motion Systems Ltd., Oxford, UK). Countermovement jump (CMJ) data for fatigue threshold monitoring were collected using portable dual-platform force plates (Hawkin Dynamics, Westbrook, ME, USA; 1000 Hz). Isometric maximal voluntary contractions (MVC) of the quadriceps and hamstrings were assessed using a TruStrength strain gauge (Hawkin Dynamics, Westbrook, ME, USA), secured to a fixed rigid structure with participants positioned at approximately 90° of knee flexion, following an equivalent set-up to Ivarsson & Cronström⁸⁵. Heart rate was monitored continuously throughout the fatigue session using a chest strap (H10; Polar Electro, Kempele, Finland). Height and mass were recorded to the nearest 0.1 cm and 0.1 kg, respectively, using a fixed wall stadiometer (Harpenden, Hertfordshire, UK) and digital scales (SECA, Hamberg, Germany).

3.3.4 Procedure

Prior to their first session, participants were provided access to an online video library detailing all exercises involved in both sessions, including the warm-up, fatigue protocol, and assessment battery, to minimise novelty effects on the day of testing ([The warm-up protocol](#); [The Fatigue protocol](#); [The RTS battery](#)). Both the Baseline and Fatigue sessions started with a standardised warm-up (Appendix 2) and a submaximal familiarisation trial of each assessment task.

3.3.4.1 Baseline testing

Participants completed three maximal trials of the full assessment battery in a randomised order: (1) CMJ; (2) single-leg vertical jump (SLVJ); (3) single-leg hop for distance (SLHD); (4) single-leg drop jump (SLDJ); isometric maximal voluntary contraction of the (5) quadriceps (QMVC) and (6) hamstrings (HMVC). Isometric contractions were always completed last within each session. Standardised verbal instructions and encouragement were provided throughout.

For unilateral tasks, a trial was deemed successful if the participant maintained single-leg stance on landing without contacting the ground with the contralateral limb or losing balance to the point of falling. Trials were excluded if the landing foot shuffled significantly, the participant fell, landing occurred on the incorrect force plate, or the contralateral limb was used to aid jump height or distance.

3.3.4.2 Fatigue Testing Session

Prior to the fatigue protocol, three maximal CMJ trials were completed to establish each participant's non-fatigued baseline (Figure 3). Fatigue was defined as a 30% reduction in CMJ height from baseline, following Tallard et al.³⁰. CMJ height was selected as a practical criterion that clinicians or assistants can measure quickly and repeatedly without specialised training, making the protocol feasible to replicate in applied settings. However, CMJ height is a proxy for neuromuscular fatigue and does not directly measure physiological impairment⁸³.

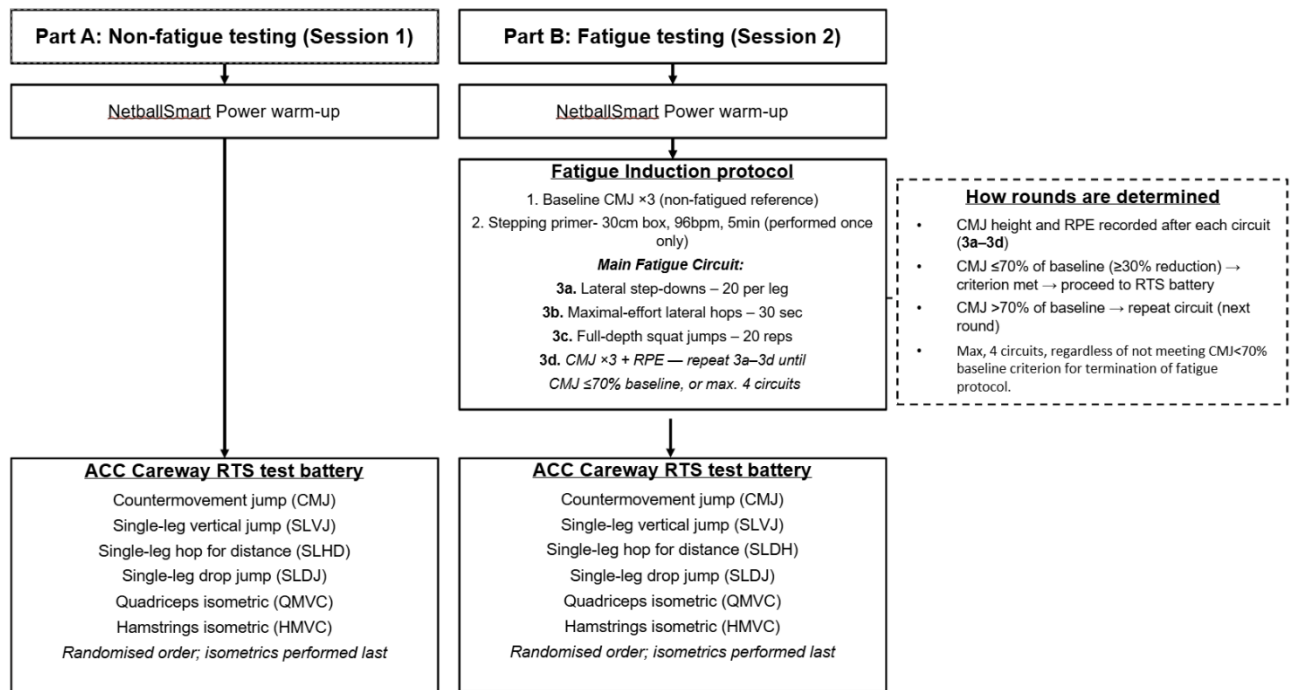


Figure 3. Baseline and fatigue session flowchart with fatigue verification.

As part of the fatigue protocol, participants first completed a five-minute continuous stepping protocol (30 cm box, 96 bpm) as a physiological primer to elevate heart rate and metabolic demand before the main fatigue circuit. The stepping protocol was completed only once. Participants then completed the main fatigue circuit: 20 lateral step-downs per leg (30 cm box), 30 seconds of continuous maximal-effort side-to-side hops, and 20 continuous motion full-depth bodyweight squat jumps, all performed as fast as possible. Following each completed circuit, participants performed three maximal CMJ trials. Ratings of perceived exertion (RPE) were recorded using Borg’s 6–20 scale following each circuit. Circuits continued until one of the following criteria was met: CMJ height fell to ≤70% of the non-fatigued baseline (≥30% reduction), or the participant withdrew due to physical discomfort or inability to continue safely. A maximum of four circuits was imposed if neither criterion was reached prior. Upon fatigue confirmation, participants immediately proceeded to the full RTS assessment battery, consistent with session 1.

3.3.5 Data Processing

A fourth-order low-pass Butterworth filter with a cut-off frequency of 15 Hz was applied to the kinetic data in Vicon Nexus, before data were imported into Visual3D (v2026.01.1 HAS Motion, ON,

Canada) for additional processing. Initial contact was identified as the first instance of ground reaction force ascending above a task-specific threshold. For the SLVJ, SLDJ, and SLHD, a threshold of 5 N was applied, whilst for the CMJ, the threshold was 25 N. For the SLDJ, final contact was defined as the second ascent above the 5 N threshold.

For each trial, outcome variables were extracted at discrete events for both limbs: initial contact, 40 ms post-initial contact, and the minimum and maximum values occurring within the landing phase. For the SLDJ, additional variables were extracted at final contact and 40 ms post-final contact. Unsuccessful trials were recorded and excluded from analysis, with only the final successful attempt for each task retained for further processing. Total number of trials per task, per participant are available in supplementary files.

3.3.6 Statistical Analysis

Statistical analyses were performed using R (R Core Team, version [4.60.0]). A hierarchical framework was used to evaluate the effect of fatigue on outcomes during an RTS assessment battery, comprising a primary outcome analysis and a secondary outcome exploratory analysis. For each RTS jump type, a single primary outcome was analysed: CMJ and SLVJ - jump height, SLHD - hop distance, SLDJ - reactive strength index (RSI), and peak force for quadriceps and hamstring MVCs. CMJ was analysed bilaterally, while other assessments were analysed unilaterally, resulting in 11 primary comparisons. All outcome variables are organised by movement task in table 7.

Table 7. Return-To-Sport Assessment Tasks and Outcome Measures

Outcome measure	Units / notes	CMJ & SLVJ	SLDJ	SLJD	QMVC/HMVC	LSI
Jump height	<i>M</i>	✓	✓			
Concentric peak force	<i>N</i>	✓				
Concentric impulse	<i>N-s</i>	✓				
Eccentric peak force	<i>N</i>	✓				
Eccentric braking impulse	<i>N-s</i>	✓				
RSI	<i>ratio</i>		✓			
Hop distance	<i>cm</i>			✓		
Peak landing force	<i>N</i>	✓	✓	✓		
Landing RFD*	<i>N/s — initial contact to peak</i>	✓	✓	✓		
Landing RFD at 40 ms*	<i>N/s — first 40 ms post-contact</i>	✓	✓	✓		
Eccentric landing impulse*	<i>N-s</i>	✓	✓	✓		
Peak isometric force	<i>N</i>				✓	
Jump/hop tasks: derived from jump height or hop distance	<i>% (Non-Dom/Dom) × 100</i>					✓

Note. CMJ = countermovement jump; SLVJ = single-leg vertical jump; SLDJ = single-leg drop jump; SLJD = single-leg jump for distance; QMVC = quadriceps maximal voluntary contraction; HMVC = hamstring maximal voluntary contraction; LSI = limb symmetry index; RSI = reactive strength index; RFD = rate of force development; MVC = maximal voluntary contraction. Dominant limb defined as preferred kicking limb (self-report at screening). * Novel outcome measure not included in standard RTS test batteries. Bolded outcome measures indicate primary outcomes as delineated in the statistical analysis.

The distinction between primary and secondary outcomes was determined *a priori*, based on metrics most frequently reported in standardised RTS protocols^{32,86}. Primary outcomes are readily quantifiable indicators of task success and are commonly reported in the literature through an LSI expression to inform RTS decision-making^{14,32,86}. Although additional force-time kinetic metrics are classified as secondary, they may offer greater mechanistic insight into movement deficits and limb symmetry. However, due to substantial interdependence among secondary variables, including these in hypothesis testing could increase the family-wise error rate and result in erroneous inferences. Accordingly, formal statistical testing was limited to primary outcomes, while secondary metrics are examined descriptively to characterise potential fatigue-related changes.

Normality was assessed using the Shapiro–Wilk test and Q–Q plots. As all variables were normally distributed, paired-samples *t*-tests were used for all comparisons. To control the family-wise error rate arising from the 11 paired comparisons, *p*-values were adjusted using the Holm correction. For each, baseline and fatigued means ($\pm$ SD), mean change, 95% CI, and Cohen's *d*_z are reported with adjusted *p*-values. Secondary analyses presented the remaining metrics where interpretation focused on effect magnitude, direction, and consistency across tasks, given the exploratory design and small sample (*n*=15). Task-specific kinetic variables (Table 7) were examined descriptively to contextualise changes in primary outcomes. Mean $\pm$ SD, mean change, percentage change, and Cohen's *d*_z are reported for baseline and fatigued conditions. Alpha was set at 0.05 for the primary analyses, and no inferential threshold was applied to secondary analyses.

3.4 Results

3.4.1 Participants

Data from one participant's fatigue session were excluded from the formal analyses due to data corruption. Consequently, inferential analyses were conducted on 15 participants. Participants were aged 23.1 ± 4.7 (range 18–34 years), with a mean height of 170.5 ± 5.9 cm and body mass of 65.1 ± 7.4 kg. Participants reported a mean training volume of 6.9 ± 2.8 h·wk⁻¹. Thirteen participants were right-leg dominant, and sport participation comprised court-based (*n*=10) and field-based (*n*=6) sports, including netball (*n*=5), hockey/football (*n*=4), touch rugby (*n* = 3), and other individual or court-based sports (*n*=4).

3.4.2 Fatigue Verification

Across the 15 participants who completed the fatigue protocol, the number of circuits required to reach the fatigue criterion ($\geq 30\%$ reduction in CMJ height) ranged from 1 to 4, with most participants (*n*=9) reaching the criterion within 2 circuits. Final-round RPE ranged from 15–20 (Borg 6–20 scale) and heart rate ranged from 172–209 bpm (mean 187.9 bpm), together indicating substantial

physiological and perceptual demand at the point of fatigue confirmation. No participants withdrew from the fatigue protocol due to physical discomfort or inability to continue. Note that fatigue-verification metrics reflect the full sample ($n = 16$); the kinetic dataset for RTS testing excludes P01 due to force-trace corruption, as reported above. Full breakdown presented in Table 8.

3.4.3 Primary outcome metrics:

Of the 11 primary comparisons, effect sizes ranged from trivial to large, with four outcomes demonstrating large effects ($d_z \geq 0.80$), two small-to-moderate effects, and five trivial-to-small effects (Table 9). Dominant-limb quadriceps peak isometric force and dominant-limb SLHD were the only primary outcome metrics that showed a significant difference. CMJ height and non-dominant SLHD demonstrated comparably large effect sizes but were not significantly different (Table 9). In contrast, SLDJ RSI, HMVC, SLVJ height, and non-dominant quadriceps strength were essentially unaffected by fatigue (d_z range -0.49 to 0.30). Full effect estimates, confidence intervals, and adjusted p -values for all comparisons are presented in Table 9.

Table 8. Fatigue verification

Participant	Dom	Pre-Fatigue CMJ (cm)	Final CMJ Achieved (cm)	% CMJ Reduction	Rounds Required	Final RPE	Final HR
P01	R	27.0	17.0	34.6	3	18	192
P02	L	27.3	14.0	48.1	4	18	180
P03	R	28.3	16.0	40.7	2	18	177
P04	R	27.7	16.0	42.9	2	18	199
P05	R	21.7	14.0	36.4	2	17	192
P06	R	28.7	13.0	53.6	4	18	192
P07	R	22.3	15.0	34.8	1	16	187
P08	R	29.0	16.0	44.8	2	16	191
P19	R	27.7	18.0	33.3	2	16	186
P10	L	29.0	26.0	13.3	4**	19	177
P11	R	28.3	17.0	41.4	4	20	197
P12	R	30.0	16.0	44.8	4	20	178
P13	R	22.7	14.0	39.1	2	15	209
P14	R	21.7	10.0	54.5	2	17	192
P15	R	25.7	16.0	36	2	20	188
Mean:	NA	26.5	15.9	39.3	2.7	17.7	189

Note. Pre-Fatigue CMH = average of three pre-fatigue CMJ trials. Final CMJ Achieved = final recorded CMJ before RTS testing. Rounds Required = number of fatigue rounds completed before criterion achievement. RPE = Borg 6–20 rating of perceived exertion recorded following the final exercise in the fatigue circuit

Table 9. Effects of Fatigue on Primary Return-to-Sport Outcomes

Variable	Baseline (Mean ± SD)	Fatigue (Mean ± SD)	% Change (95% CI)	Effect (Cohen's dz)	p (Holm)
CMJ Jump Height	0.25 ± 0.05	0.23 ± 0.04	-10.4 (-0.05 – -0.01)	-0.81 (Large)	0.057
SLVJ Height (Dom)	0.11 ± 0.02	0.10 ± 0.02	-7.4 (-0.02 – 0.00)	-0.48 (Small)	0.579
SLVJ Height (Non-Dom)	0.11 ± 0.03	0.10 ± 0.02	-8.6 (-0.02 – 0.00)	-0.49 (Small)	0.579
SLHD Distance (Dom)	46.97 ± 17.17	37.51 ± 13.78	-17.3 (-15.43 – -3.50)	-0.85 (Large)	0.041*
SLHD Distance (Non-Dom)	45.06 ± 15.70	34.58 ± 12.49	-20.2 (-17.49 – -3.47)	-0.80 (Medium)	0.055
SLDJ RSI (Dom)	0.27 ± 0.12	0.26 ± 0.11	4.3 (-0.05 – 0.04)	-0.09 (Trivial)	1.000
SLDJ RSI (Non-Dom)	0.27 ± 0.12	0.26 ± 0.11	4.7 (-0.06 – 0.05)	-0.06 (Trivial)	1.000
QMVC Peak Force (Dom)	457.72 ± 113.13	411.60 ± 100.56	-9.8 (-61.97 – 30.28)	-1.55 (Large)	< .001*
QMVC Peak Force (Non-Dom)	415.67 ± 87.54	397.73 ± 98.05	-4.1 (-52.42 – 16.55)	-0.28 (Small)	1.000
HMVC Peak Force (Dom)	253.35 ± 39.89	248.67 ± 47.62	-1.8 (-20.21 – 10.86)	-0.16 (Trivial)	1.000
HMVC Peak Force (Non-Dom)	239.81 ± 41.99	249.64 ± 44.30	4.8 (-7.80 – 27.47)	0.30 (Small)	1.000

Note. Dom = dominant limb; Non-Dom = non-dominant limb; CMJ = countermovement jump; SLVJ = single-leg vertical jump; SLHD = single-leg hop for distance; SLDJ = single-leg drop jump; RSI = reactive strength index; QMVC/HMVC = quadriceps/hamstring maximal voluntary contraction. p = unadjusted p-value; p (Holm) = Holm-adjusted p-value across 11 comparisons. * = significant after Holm correction ($\alpha = .05$).

3.4.4 Secondary Outcomes

For the secondary kinetic outcomes, effect sizes ranged from trivial to large, with ten comparisons demonstrating medium-to-large effects (Table 10). The complete dataset, including baseline and fatigued means, mean and percentage changes, 95% confidence intervals, and effect sizes, is provided in Supplementary Table S1. During the CMJ, fatigue reduced landing RFD during the first 40 ms of contact (-9.8%, $dz = -0.88$), as well as the entire landing phase (-9.2%, $dz = -0.98$), accompanied by reductions in concentric impulse (-5.6%, $dz = -0.88$) and peak landing force (-4.4%, $dz = -0.60$). During the SLDJ, eccentric peak force decreased bilaterally (dominant: -7.3%, $dz = -0.64$; non-dominant: -7.2%, $dz = -0.91$), alongside comparable reductions in eccentric braking impulse (dominant: -9.2%, $dz = -0.85$; non-dominant: -8.3%, $dz = -0.96$). Similarly, dominant-limb eccentric peak force decreased during the SLVJ (-7.2%, $dz = -0.70$), while non-dominant concentric impulse was modestly reduced (-6.6%, $dz = -0.55$). All remaining secondary outcomes demonstrated trivial-to-small effects ($dz \leq 0.35$).

Table 10. Secondary Exploratory Biomechanical Outcomes (Medium-to-Large Effects)

Variable	Baseline (Mean +/- SD)	Fatigue (Mean +/- SD)	% Change	95% CI of Change	Effect (Cohen's dz)
CMJ					
Concentric Impulse	323.7 ± 44.60	305.1 ± 40.8	-5.56%	-30.47, -6.88	-0.88 (Large)
Peak Landing Force	2360.5 ± 377.08	2255.7 ± 384.4	-4.42%	-201.06, -8.46	-0.60 (Medium)
Landing RFD	35669.6 ± 14531.2	32069.1 ± 14087.6	-9.77%	-5873.75, - 1327.40	-0.88 (Large)
Landing RFD (0-40ms)	17454.8 ± 10662.4	15967.2 ± 10954.1	-9.16%	-2326.14, - 648.97	-0.98 (Large)
SLVJ					
Eccentric Peak Force (Dom)	1053.6 ± 161.6	974.4 ± 162.2	-7.22%	-142.22, -16.20	-0.70 (Medium)
Concentric Impulse (Non-Dom)	307.7 ± 60.1	283.2 ± 39.4	-6.56%	-50.25, 1.32	-0.55 (Medium)
SLDJ					
Eccentric Peak Force (Dom)	1738.3 ± 205.3	1603.7 ± 233.1	-7.34%	-250.35, -18.82	-0.64 (Medium)
Eccentric Peak Force (Non-Dom)	1695.2 ± 240.3	1573.9 ± 266.0	-7.19%	-194.97, -47.40	-0.91 (Large)
Eccentric Braking Impulse (Dom)	224.5 ± 43.3	202.9 ± 40.6	-9.23%	-35.65, -7.44	-0.85 (Large)
Eccentric Braking Impulse (Non-Dom)	220.2 ± 44.1	201.5 ± 43.1	-8.33%	-29.45, -7.86	-0.96 (Large)

Note. Dom = dominant limb; Non-Dom = non-dominant limb; CMJ = countermovement jump; SLVJ = single-leg vertical jump; SLDJ = single-leg drop jump; RFD = rate of force development. Effect magnitude classified per Cohen's dz thresholds. Secondary outcomes were analysed descriptively; no inferential (p-value) threshold was applied. Full results for all 47 secondary comparisons, including trivial and small effects, are presented in Supplementary Table S1.

3.5 Discussion

The primary aim of this study was to determine the acute effects of a standardised neuromuscular fatigue protocol on lower-limb kinetic and performance outcomes during RTS testing in recreationally active female athletes. We hypothesised that fatigue would negatively affect both traditional performance metrics and force-time-derived kinetic outcomes. The primary findings were that fatigue significantly reduced dominant-limb quadriceps strength and dominant-limb hop distance, while several additional performance outcomes demonstrated moderate-to-large reductions. Secondary analyses revealed a broader pattern of fatigue-related kinetic impairment, particularly within eccentric force production, braking impulse, and landing RFD variables, despite relatively limited changes in several traditional performance measures. These findings suggest that fatigue may alter underlying neuromuscular function to a greater extent than what is revealed from conventional RTS performance outcomes alone, supporting the potential value of incorporating descriptive kinetic assessment into RTS decision-making.

3.5.1 Fatigue verification:

A key requirement of this study was to induce a meaningful fatigue state before RTS assessment. The protocol was effective as participants showed substantial physiological, perceptual, and performance responses consistent with fatigue. Heart rates at fatigue cessation were high to

approaching maximal, and perceived exertion scores ranged from 'hard' to 'very hard', indicating exercise at or near maximal intensity. Comparable physiological responses have been reported in previous fatigue protocols that replicate sport-related neuromuscular fatigue, suggesting that the present protocol elicited a level of fatigue similar to that observed in prior ACL research^{30,34,43,69}. A decline in CMJ performance, the operational fatigue criterion, further supported effective fatigue induction. The magnitude of CMJ decline was akin to that reported by Tallard et al. (2021), from which this protocol was adapted. This consistency provides external validation that participants entered post-fatigue RTS testing with neuromuscular impairment comparable to previous ACL studies. The variability in the number of circuits required to reach the fatigue threshold (1-4) indicates substantial inter-individual differences in fatigue resistance and suggests that similar performance thresholds may have been reached through different physiological mechanisms. The observed range in circuits required to reach fatigue threshold (1-4) demonstrates considerable inter-individual variability in fatigue resistance, indicating that participants may have reached similar thresholds via distinct physiological mechanisms. As a result, the contributions of central and peripheral fatigue, metabolic disturbance, and localised muscle fatigue likely varied between individuals, which may account for the outcome patterns in this study. The protocol primarily reduced quadriceps force production, with hamstring strength unaffected, indicating greater loading of knee extensors. Fatigue-related declines were more pronounced in reactive tasks involving rapid force regulation than in maximal strength or hop-distance measures. Protocols that induce greater physiological or whole-body fatigue, or more balanced quadriceps and hamstring loading, may yield different RTS outcomes. Further research should determine whether combining neuromuscular and physiological fatigue stimuli increases the sensitivity of RTS assessments to fatigue-related impairments while maintaining clinical feasibility. All but one participant met the study criteria for fatigue. The relative influence of central and peripheral fatigue, metabolic disturbance, and exercise volume likely varied between individuals⁸³. These differences are further reflected in the mechanistic factors affecting CMJ performance, such as variations in strength and stretch-shortening cycle profiles between athletes. Fatigue should therefore not be interpreted as a uniform construct across the sample.

It is also important to note that while CMJ performance is a practical proxy for neuromuscular fatigue, it does not directly measure physiological impairment⁸³. Reductions in jump height are sensitive to acute fatigue, but CMJ performance is also determined by tendon stiffness, stretch-shortening cycle efficiency, motivation, and movement strategy^{87,88}. As a result, identical fatigue thresholds may reflect differing underlying physiological mechanisms. This variability may account

for the greater fatigue-related changes observed in reactive kinetic measures compared to maximal strength or hop-distance outcomes, and for the decline in quadriceps force with minimal change in hamstring force. Thus, some individuals may maintain jump performance despite neuromuscular dysfunction, while others may show large reductions despite similar fatigue. Despite mechanistic concerns, use of CMJ average score, compared to max displacement, is seemingly a more sensitive metric to assess neuromuscular fatigue⁸⁹. Collectively, elevated heart rates, high RPE, and marked reductions in CMJ performance indicate that participants entered post-fatigue testing under substantial physiological stress. Although the nature and magnitude of fatigue likely varied, the protocol appeared to elicit a fatigue state sufficient to assess its effects on RTS performance and kinetics.

3.5.2 Performance metrics (non-uniform decrease pattern)

Performance-based outcomes remain the dominant approach to RTS assessment because these metrics are accessible and clinically interpretable, reflecting physical qualities required across sporting contexts^{14,86}. Their sensitivity to neuromuscular fatigue is less established. Prior fatigue-RTS studies generally report reduced hop and jump performance following the stimulation of fatigue, regardless of protocol type^{30,45,50,64}, though the degree of decline varies by task, protocol, and population^{34,45}. The present study extends previous research on fatigue-related performance outcomes by concurrently analysing multiple RTS-relevant performance and force-related measures within a single fatigued cohort.

Two of eleven performance outcomes demonstrated a difference between fresh and fatigued states, these being dominant-limb QMVC (−9.8%) and SLHD (−17.3%). Despite clear physiological and perceptual evidence of fatigue, differences between fresh and fatigued states were not clear in any of the other performance metrics analysed. This pattern held regardless of limb dominance or movement plane, indicating that fatigue did not affect all RTS tasks equally. This selective impairment aligns with the concept that RTS tasks vary in the physiological attributes they assess. Force-dependent tasks, such as QMVC and SLHD, exhibited the most pronounced decrements, whereas the stretch-shortening cycle-dependent SLDJ appeared resistant to fatigue. This occurred despite a marked decline in CMJ performance during the fatigue protocol, confirming successful fatigue induction. Similar task-specific dissociations have been documented, with different hop and jump tests demonstrating varying sensitivity to fatigue can be found within the same cohort across varying performance jump tasks^{38,45,53,65}. However, the stability of an outcome measure does not necessarily indicate that the underlying movement remains unaffected. Fatigue-induced alterations

in landing mechanics, force absorption, and joint loading have been observed even when overall task performance is retained^{38,43,50,63}. Similarly, Kotsifaki et al.^{81,90} reported that hop distance and symmetry may obscure persistent biomechanical deficits following ACLR.

3.5.3 Force-time secondary kinetic outcomes

The clearest fatigue-related impairment was observed during the SLDJ, when under fatigued conditions, eccentric peak-force and braking impulse declined bilaterally by up to 9% despite minimal change in RSI. If RSI were considered in isolation, this task may have appeared relatively resistant to fatigue; however, the reduced eccentric force absorption capacity indicates that athletes maintained global task performance despite altered landing mechanics. This suggests that preserved RTS performance may not necessarily reflect preserved force regulation capacity⁷⁴.

This distinction reflects a broader limitation of conventional RTS outcomes, which primarily quantify task completion and global performance characteristics, while providing limited insight into the magnitude, attenuation, and regulation of forces following ground contact in hop/jump tasks^{91,92}. Force-time metrics may therefore offer additional sensitivity to fatigue-related alterations occurring within the same functional tasks used during RTS assessment.

A similar pattern was observed during the CMJ and SLVJ. In the CMJ, concentric impulse declined, but the largest effects occurred during landing, where RFD overall and within 40 ms of contact both fell by roughly 9-10%. Peak landing force showed a smaller reduction. Dominant-limb eccentric peak force during the SLVJ also declined, comparable to the SLDJ (Table 10). These findings suggest that fatigue affected both force production and force absorption, with the greatest effects on early force-time characteristics of landing rather than on peak force magnitude. Given the short timeframe in which these early force-time characteristics occur, these alterations may reflect changes in rapid neuromuscular force regulation rather than conscious movement modification; however, this interpretation remains speculative without accompanying electromyographic or kinematic data.

Previous fatigue research has primarily identified altered landing strategies through kinematic outcomes, including increased dynamic knee valgus, reduced knee flexion, and altered movement control strategies^{38,40,43}. The present findings complement these studies by demonstrating that fatigue-related changes may also be evident within the force-time characteristics underlying movement execution. Given that ACL injuries commonly occur shortly after ground contact during landing, cutting, and deceleration tasks⁹³, reductions in rapid force regulation may represent a relevant mechanical alteration. However, this interpretation remains hypothesis-generating rather than evidence of increased injury risk.

The hamstrings are critical for dynamic knee stability, especially in injury prevention and rehabilitation⁹⁴. Hamstring force generation remained unchanged after fatigue induction. (dominant: -1.8%, $dz = -0.16$; non-dominant: 4.8%, $dz = -0.30$). This may reflect a fatigue protocol that primarily loaded the quadriceps, as indicated by reduced quadriceps force generation (dominant: -9.8%, $dz = -1.55$; non-dominant: -4.1%, $dz = -0.28$). Alternatively, the RTS assessment tasks may not have sufficiently challenged knee flexor function to reveal fatigue-related deficits. These findings are limited to a healthy cohort and do not reflect the neuromuscular impairments or hamstring strength deficits frequently observed after ACL reconstruction using hamstring autograft⁹⁴.

3.5.4 LSI/Dominance

Consistent with previous findings from fatigue-related RTS assessment studies involving limb symmetry measures, in this study uniformly both limbs decreased comparably per task, irrespective of dominance^{30,38,64}. During the SLDJ, eccentric peak force and braking impulse declined by near-identical magnitudes in both limbs, indicating a largely symmetrical fatigue response. In contrast, the SLVJ demonstrated a more asymmetrical pattern, with fatigue-related reductions in dominant-limb eccentric peak force and non-dominant-limb concentric impulse. Thus, while some tasks produced limb-specific changes that could alter inter-limb ratios, others produced bilateral decrements with minimal effect on symmetry. This distinction is clinically important because LSIs are among the most frequently used criteria for RTS decision-making^{14,32,86}. By design, LSI quantifies the difference between limbs rather than the absolute capacity of either limb. Consequently, when fatigue affects both limbs, as observed in the SLDJ, substantial reductions in force production and force attenuation can occur without meaningful changes in symmetry. In such cases, an athlete may appear functionally unchanged according to LSI, despite demonstrating a genuine decline in overall neuromuscular capacity. Consequently, symmetry should not be interpreted as synonymous with recovery⁹⁵. The present findings extend this concern to the acutely fatigued state, demonstrating that bilateral reductions in landing-force capacity may occur without being detected by ratio-based measures. Although limb dominance is an imperfect surrogate for injury status in healthy cohorts^{95,96}, the findings demonstrate that symmetrical performance does not necessarily indicate optimal function. Consequently, LSI may be insensitive to fatigue-induced decrements when both limbs decline similarly. Therefore, symmetry measures should be interpreted alongside assessments of absolute performance and movement quality rather than as a standalone indicator of readiness for sport.

3.5.5 Clinical implications

Fatigue reveals neuromuscular deficits not consistently detected by conventional RTS performance measures. Traditional metrics such as hop distance, jump performance, and limb symmetry are accessible and clinically interpretable, but do not fully capture an athlete's capacity to absorb and regulate forces during demanding movements. Including additional force-time metrics, especially those assessing eccentric force production, braking impulse, and early landing force regulation, into RTS assessments may provide further insight into movement capacity under physiological stress. This is relevant when evaluating athletes returning to high-demand sports involving repeated landing and deceleration under fatigue. These results underscore the need to interpret RTS outcomes in the context of absolute performance, movement strategy, and fatigue state, rather than relying solely on thresholds or symmetry indices. Athletes may show acceptable limb symmetry or complete tasks despite reductions in neuromuscular capacity. Further research is needed to determine whether fatigue-related kinetic changes affect injury risk, sport performance, or RTS decisions. Future longitudinal research in diverse ACLR populations (e.g., varying age, sex, sport type, and sporting level) incorporating integrated kinetic–kinematic assessments is needed to determine the clinical utility of fatigue-informed RTS evaluation.

3.5.6 Limitations

The findings of this study should be interpreted with several limitations in mind. Firstly, the study sample comprised recreationally active female athletes without prior ACL injury or reconstruction. This approach enabled assessment of fatigue-related neuromuscular responses without confounding from injury or rehabilitation. However, the findings likely do not completely translate to athletes who have undergone ACL reconstruction or those with ongoing neuromuscular deficits. Further research should assess whether comparable fatigue-related kinetic changes occur in clinical RTS populations. Secondly, the protocol induced acute neuromuscular fatigue but may not reflect the multifactorial fatigue experienced during competition or repeated exposure. While fatigue was confirmed by physiological, perceptual, and performance measures, the CMJ fatigue criterion is an indirect proxy of neuromuscular fatigue and does not distinguish between the physiological mechanism contribution to performance decline. Consequently, the specific contributions of central and peripheral fatigue, metabolic factors, and movement strategy remain unclear. The lack of concurrent kinematic and electromyographic data limits interpretation of the mechanisms underlying changes in force-time characteristics. Future studies should integrate kinetic, kinematic, and neuromuscular assessments to clarify how fatigue influences movement control. Finally, the kinetic analyses were exploratory and included multiple secondary outcomes. Effect sizes and statistical corrections were applied, but these results are hypothesis-generating rather than

conclusive. Further research is needed to determine whether fatigue-related changes in force regulation affect sport performance, injury risk, or RTS outcomes.

3.6 Conclusion

Fatigue-induced alterations in movement strategy were more evident in force-time characteristics than in conventional RTS performance outcomes. Measures of eccentric force absorption and rapid landing-force regulation identified deficits that were not consistently detected by traditional metrics such as hop performance, jump height, or limb symmetry. These findings suggest that athletes may maintain apparent RTS performance despite underlying changes in force regulation capacity.

Evaluating how movement is performed, rather than solely whether a task is completed successfully, may therefore provide a more sensitive assessment of fatigue-related neuromuscular function.

Additional research is necessary to determine whether fatigue-related kinetic alterations influence RTS outcomes, sport performance, or subsequent injury risk across diverse population cohorts (ACLR status, sex, age, sport type, and sporting level).

Chapter 4: Discussion and Conclusion

4.1 Overview of main findings

This thesis investigated the influence of fatigue on anterior cruciate ligament (ACL) return-to-sport (RTS) assessment outcomes, and the extent to which current RTS testing practices account for these effects. The research comprised a scoping review of existing literature (Chapter 2) and an experimental study employing a clinically feasible fatigue protocol within a multifactorial RTS assessment battery (Chapter 3). The findings indicate that fatigue affects RTS outcomes and may impact the interpretation of athlete readiness.

The scoping review synthesised twelve studies and found that fatigue commonly impaired hop performance, movement quality, and landing biomechanics. Substantial heterogeneity in fatigue protocols, verification methods, assessment tasks, and outcome measures limited confidence in the magnitude and consistency of these effects. Methodological inconsistency, rather than disagreement regarding the influence of fatigue, currently constrains interpretation and comparison across studies.

The experimental study addressed heterogeneity in fatigue protocols and fatigue-verification methods identified in the scoping review by implementing a standardised, clinically feasible fatigue protocol, verified by reductions in CMJ performance and increases in physiological and perceptual fatigue markers. Significant reductions were observed in dominant-limb quadriceps strength and SLHD, whereas most conventional RTS performance-based outcomes (e.g. jump height, hop distance, RSI and strength) were unchanged. Secondary kinetic variables related to force absorption and landing control, including eccentric peak force, braking impulse, and landing rate of force development, demonstrated consistent moderate-to-large declines with fatigue. These findings indicate that fatigue alters neuromuscular function in ways not consistently detected by conventional performance-based RTS outcome measures.

Collectively, these studies demonstrate that fatigue modifies the relationship between observed RTS performance and underlying neuromuscular capacity. Conventional RTS assessment evaluates performance under rested conditions, whereas fatigued assessment determines whether performance is maintained under increased physiological demand. The following sections address the clinical relevance of this divergence and identify areas requiring further evidence.

4.2 Conventional versus fatigued assessment: why the distinction matters

RTS assessments aim to determine if an athlete has recovered function sufficiently to progress safely onto dynamic sporting activities. Often this stage is viewed as terminal screening within recreational populations, however clinical consensus is pushing towards a return-to-activity continuum, where sport is the pen-ultimate stage to return-to-performance (often associated only with elite/high functioning athletic populations)⁷⁶. However, readiness to return, itself cannot be measured directly, as it represents a multidimensional construct encompassing physical capacity, movement quality, psychological readiness, tissue recovery, sport-specific demands, and contextual factors. No single assessment can quantify all these components simultaneously, so clinicians instead rely on surrogate measures such as quadriceps strength, hop distance, and limb symmetry. This introduces a construct-validity issue, as these tests assess controlled performance rather than readiness itself, and equivalence between the two is assumed rather than established. The findings of this thesis indicate that readiness as an assumption may not be valid. The fatigue-verification method used in the experimental study ($\geq 30\%$ CMJ decline) represents a neuromuscular proxy measure rather than an absolute indicator. Whilst this proxy was achieved for 14 out of 15 participants with substantial simultaneous physiological markers (RPE 15-20; 172-209 bpm), CMJ jump height is known to be influenced by tendon stiffness, stretch-shortening cycle efficiency, and movement strategy^{87,88}. The observed dissociation between stable performance and declining kinetics, despite the use of an imperfect proxy, reinforces the central finding: surrogate measures of readiness may not accurately reflect the underlying capacity they are intended to represent.

The scoping review demonstrates the extent of this issue at the higher level. Among the twelve included studies, no two studies used the same fatigue protocol, verification criterion, or outcome battery. This variation exists within a broader literature reporting over thirty different RTS test-battery combinations within New Zealand alone, with no consensus on which best reflects readiness¹⁴. The problem is not twelve studies with differing conclusions about fatigue, rather the problem the scoping review highlights is the operationalisation of fatigue across multiple, inconsistent methods, limiting comparison between studies and the development of consensus. The methodological heterogeneity identified in the scoping review highlights the need for standardised approaches to inducing fatigue and assessing readiness if findings are to be meaningfully compared across studies.

The limitations of single tests have practical as well as conceptual implications. Quadriceps strength testing is a recognised predictor of functional recovery after ACL reconstruction, but maximal

strength represents only one aspect of sporting performance⁹⁷. Athletes must also generate, absorb, and regulate force during multidirectional movement. Hop testing presents a similar limitation: successful completion of a single-leg hop confirms task achievement but does not reveal the movement strategy, and compensation can mask deficits⁹¹. These limitations do not negate the value of the tests; each assesses a component of a multidimensional construct. The central question is whether tests performed under rested conditions alone provide a sufficient basis for judging readiness and whether we are interpreting these tests effectively to offer greater understanding of task capacity. The experimental findings indicate that this is not always the case, as fatigue altered kinetic data without affecting task completion. The divergence between performance and kinetics is addressed in the following section.

4.3 Performance and kinetic outcomes: why both matter

This study assessed conventional performance and kinetic outcomes in both rested and fatigued states. The primary finding is the marked divergence between these two sets of results, rather than the absolute values of either outcome.

4.3.1 Stability of performance outcomes

Among the eleven primary performance comparisons, only dominant-limb quadriceps peak isometric force and dominant-limb single-leg hop distance demonstrated statistically significant fatigue-related declines following correction for multiple comparisons. CMJ height and non-dominant hop distance exhibited similarly large effect sizes without reaching significance. Reactive strength index, hamstring strength, single-leg vertical jump height, and non-dominant quadriceps strength were not meaningfully affected. Thus, most outcomes commonly used to assess readiness for RTS remained stable under fatigue.

MVC and SLHD were largely maintained after the fatigue protocol. Both MVC and SLHD are self-paced assessments that permit greater time for force development, minimising reliance on rapid neuromuscular regulation. In contrast, tasks such as the SLDJ require force production and absorption within short ground contact times, increasing demands on reactive neuromuscular control^{88,98}. Fatigue-related impairments are therefore more likely to be detected during reactive tasks, as the ability to rapidly regulate force may decline even when maximal force generation is preserved⁸³.

Significant fatigue-related declines were limited to the dominant limb for selected outcomes. While we don't have the data to explain these findings, they may suggest a limb-dependent fatigue response, as the dominant limb is subject to greater cumulative loading due to preferential use in

sport-specific actions such as kicking, cutting, and take-off, increasing susceptibility to fatigue^{99,100}. Alternatively, these findings may result from statistical threshold effects. With a modest sample size, small bilateral declines may have occurred, but only the dominant limb exceeded the threshold for statistical significance due to biological variability and limited power. The current data do not distinguish between these explanations, and the observed asymmetry should be considered preliminary.

4.3.2 Decline of kinetic outcomes

Unlike the primary performance outcomes (jump height, hop distance, RSI and strength), the secondary measures consisted of force-time-derived kinetic intended to provide greater mechanistic insight into movement execution. Kinetic outcomes demonstrated consistent fatigue-related declines across these secondary measures, with ten comparisons showing medium-to-large reductions. Eccentric peak force and braking impulse decreased bilaterally during the single-leg drop jump; landing rate of force development declined during the CMJ; concentric impulse and peak landing force were also reduced. These variables reflect force absorption and control during landing and declined even when task performance was maintained. This pattern aligns with established mechanics of non-contact ACL injury. The critical loading window during landing occurs within approximately 40 ms of ground contact, making rapid force control more relevant to injury risk than overall task completion⁹³. In this study, landing rate of force development within the 0–40 ms window declined most under fatigue, with similar reductions in eccentric force and braking impulse. While this thesis does not test the causal link between fatigue and injury risk, this finding may indicate that fatigue alters movement characteristics most relevant to the accepted injury mechanism, even where participants meet conventional RTS criteria.

Interpretation of these findings is limited by the influence of jump height on landing kinetics. Normalising impact kinetics to take-off or jump height can alter or reverse reported outcomes⁹². As CMJ height declined modestly with the kinetic variables in this study, it remains unclear whether the observed reductions reflect true decreases in force-absorption capacity or are attributable to lower jump height. Kinetic variables were not normalised to take-off height in the present analysis; therefore, future research should incorporate this approach to determine whether the observed changes persist independently of jump height.

4.3.3 Limb symmetry index and the limits of bilateral comparison

LSI is a widely used RTS criterion, but the present findings highlight a limitation of its application under fatigue. During the single-leg drop jump, both eccentric peak force and braking impulse declined to a similar extent in each limb, aligning with previous research indicating that bilateral symmetry is often maintained because both limbs deteriorate concurrently^{30,38}. As LSI measures inter-limb difference rather than absolute performance, athletes may satisfy symmetry thresholds despite bilateral reductions in landing-force capacity. This observation across the studies remains preliminary, as each study was not implicitly designed to assess symmetry. Although fatigue is generally expected to affect both limbs concurrently, this may not be the case following ACL reconstruction, where limb-specific fatigue responses may persist. Therefore, the ability of LSI to detect meaningful changes under fatigued conditions remains uncertain and warrants further investigation.

4.4 Clinical implications

The findings of this thesis do not indicate that conventional RTS testing should be discontinued. Quadriceps strength, hop performance, and limb symmetry remain accessible, reliable, and clinically feasible, and the present data do not dispute their continued use as a basis for RTS decision-making. However, the results indicate that clinicians should look beyond performance-based metrics alone, as a stable rested-state outcome does not necessarily reflect preserved neuromuscular capacity. Clinicians should exercise caution when interpreting symmetrical or unchanged performance scores as evidence of full recovery, particularly regarding force-absorption relevant to landing control. In this study, these specific qualities declined while task-based scores remained unchanged.

The main practical implication is that fatigue testing does not require universal application to be effective. The scoping review identified substantial variation in fatigue protocols, many of which are impractical for routine clinical use due to equipment or time demands. Incorporating fatigue testing into every RTS assessment would introduce logistical challenges without clear evidence regarding optimal protocol. Current evidence supports a targeted approach, with fatigue-based assessment likely to be most valuable where the risk of incorrect RTS decisions is highest, such as immediately prior to return to unrestricted competition. The staged approach is synonymous with the RTS framework outlined by the Panther Symposium on anterior cruciate ligament injuries¹⁰¹. However, this recommendation extends beyond the present data. The experimental cohort comprised recreationally active, uninjured females, not athletes in staged ACL rehabilitation. Therefore, the suggestion that fatigue testing is most valuable at a specific point in rehabilitation is an inference

based on mechanism, not a tested outcome, and should be considered a hypothesis for clinical practice.

Where fatigue testing is implemented, these findings do not necessitate the routine use of laboratory-grade force plates or motion capture systems. The additional clinical value observed in the present study arose from assessing performance under fatigued conditions using established RTS outcome measures, rather than from the use of advanced biomechanical instrumentation. Clinicians should incorporate a structured fatigue component into late-stage RTS assessment, where feasible, using a standardised protocol with predefined fatigue criteria. They should also interpret preserved LSI or unchanged hop scores after fatigue with caution. As shown in Section 4.3.3, symmetry-based and completion-based scores may remain stable even when force absorption and control have declined in both limbs. Therefore, a stable score after fatigue should be considered reassuring but not definitive.

4.5 Strengths and limitations

This thesis has several strengths. The two studies were designed sequentially, with the methodological heterogeneity identified in the scoping review informing the standardised experimental protocol. This approach ensured a coherent programme of work. The scoping review is, to the author's knowledge, the first to systematically map fatigue protocols specific to ACL RTS assessment, and its clinical-feasibility framework provides a practical basis for protocol selection. The experimental study used a descriptive, effect-size-led analysis strategy appropriate for the small sample, minimising the risk of misinterpretation while allowing exploration of novel force-time metrics.

There are several limitations that apply to the thesis. The most significant is practical: the research was student-led and conducted within a limited timeframe, which precluded use of a clinical ACLR cohort. ACLR patients are not readily available and present at variable points in rehabilitation, requiring matching on time since surgery, graft type, and rehabilitation stage to avoid confounding. These requirements, combined with restrictive screening and slow recruitment, were not feasible within the project timeframe. The use of an uninjured cohort was therefore a resourcing decision, and the clinical staging recommendation in Section 4.4 and the generalisability limitation should be considered provisional. Additional conceptual limitations arose from the same time and resource constraints. The fatigue protocol used repeated countermovement jumps and a structured functional circuit for standardisation and clinical accessibility, but this does not reflect the multidirectional, sport-specific fatigue experienced during training or competition. A single acute bout also does not capture cumulative fatigue across a match or season. Evidence on the timing of

ACL injuries also does not clearly support a cumulative-fatigue mechanism: injuries in professional football cluster in the first half of matches¹⁰², and secondary ACL injuries across professional sports show no clustering by game or season quarter¹⁰³. As timing is only indirect evidence and fatigue was not measured in these studies, the relationship between fatigue and ACL injury remains inconclusive, and the altered landing kinetics observed after a single acute bout here cannot be causally linked to injury risk. In this healthy cohort, fatigue-related declines in force production and braking occurred alongside reduced jump height, which lowers landing demand, so lower landing forces cannot by themselves be taken to indicate lower or higher injury risk. Comparable declines may carry different consequences depending on the athlete's starting capacity and neuromuscular control: if fatigue degrades control, loads may be regulated and distributed less effectively even when net force is lower, which could increase risk, but this cannot be confirmed without kinematic and electromyographic data.

The fatigue criterion ($\geq 30\%$ CMJ reduction) was verified on portable Hawkin force plates, whereas CMJ height in Table 9 was measured on the Bertec treadmill force plates during RTS testing, so the two values are not comparable and the smaller change in Table 9 does not represent the magnitude of fatigue at the criterion. The RTS battery began immediately after fatigue was confirmed, but task order was randomised and task duration was not standardised, as some participants needed multiple attempts to achieve valid landings. The interval between fatigue confirmation and each task was therefore not recorded and varied between participants, however ultimately minimised by instruction from researchers during collection. Partial recovery before later tasks may have occurred, and the reported effects may underestimate the fatigued state, although declines in landing kinetics and quadriceps force indicate that fatigue persisted in some outcomes.

Testing was conducted in a single session without controlling for menstrual cycle phase in this all-female sample, a variable known to influence neuromuscular performance^{104,105}, and potentially contributing unknown variance. The clinical feasibility framework developed in Chapter 2 has not been validated for reliability or applicability across settings and is used here as a structuring tool rather than a clinical instrument. Neither study included longitudinal follow-up, so the relationship between fatigue-related kinetic changes and injury risk over time remains unaddressed.

4.6 Conclusion

This thesis investigated whether fatigue influences ACL RTS assessment outcomes and whether current testing practices adequately account for its effects, demonstrating that fatigue alters RTS outcomes and that current testing practices do not fully account for these changes. Conventional performance-based RTS outcomes were largely preserved under fatigue, while kinetic measures of force absorption and landing control declined consistently. Suggesting a divergence between task completion and neuromuscular capacity that rest-performance-only testing is not designed to detect. This divergence does not invalidate conventional RTS assessment, which remains a feasible and necessary foundation for clinical decision-making, but it does indicate that a stable or symmetrical result obtained at rest should not automatically be read as confirmation of full recovery. Selectively incorporating a feasible fatigue component into RTS assessment, particularly where the consequences of an incorrect decision are greatest, offers a practical solution to close part of this gap, while larger, clinically representative, and longitudinal studies are needed before fatigue testing can be recommended as a standard part of ACL RTS practice.

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Appendices

Appendix 1: Ethics Approval, Auckland University of Technology Ethics Committee



2 October 2025

Kelly Sheerin
Faculty of Health and Environmental Sciences

Dear Kelly

Re Ethics Application: **25/248 Cleared but not ready? Investigating the impact of fatigue on testing used in ACL injury return-to-sport assessment**

Thank you for your responses to AUTEC's conditions.

Your ethics application has been approved for three years until 1 October 2028.

Non-Standard Conditions of Approval

1. Remove "koha" from the Information Sheet.
2. In the Consent Form include a specific yes/no question for the participant to receive a copy of their individual results.
3. In the advertisement please replace "primary" with "student" researcher so that the public understand that this is research undertaken by a student.

Non-standard conditions do not need to be submitted to or reviewed by AUTEC unless requested but must be completed before commencing your study.

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 the Secretariat at 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

Cc: fjs8728@autuni.ac.nz

Appendix 2: Netball Smart Power Warm-up

NETBALLSMART POWER WARM-UP



ACC SportSmart



This shortened warm-up is ideal for the tournament setting where time is limited and a full warm-up is not necessary for every game.

	NetballSmart Power Warm-Up	Time/Distance/Reps
Part B: Running Warm-Up Place 2 cones out every 3 metres between base line and centre court.	5. Running Straight Ahead. Run to centre of court and back. Repeat. You can vary direction of the running path as it happens in a Netball game.	2 x 15 metres
	8. Running – Circling Partner and Shoulder Contact. Run to first cone, side shuffle inwards and around partner and back out to cone. Run to next cone, side shuffle to the middle, jump and shoulder contact. Land in good stable position. Continue length of 15m and back.	2 x 15 metres
	10. Running – Quick Forwards and Backwards Sprints. Run to second cone and back to first cone. Repeat 2 cones forwards one back for length of 15m and back.	2 x 15 metres
Part C: Dynamic Preparation	11. Squats i. Squats, calf raise and body extension ii. Single leg squats each leg	5 each side 3 each side
	12. Walking Lunges. Walking lunges, calf raise and body extension	5 each side
	13. Lateral jump. Jump sideways 1m off one leg and land on other leg. Land in SBP on 1 leg. Hold for 1 second.	3 each side
Part D: Netball Specific Preparation	15. Running, Stopping and Jump, Turn and Land. Run to first cone at 75-80% speed and stop double foot landing and jump 180 degrees, land in SBP and return. Run to next cone and do 1-2 foot landing. Jump 90 degrees and land in SBP and return. Continue length of 15 metres and back.	2 x 15 metres
	17. Prop, Prop and Stick. Prop from one foot to another and then "stick" final landing for 2 seconds in a stable body position.	15 metres and jog back

Numbering is consistent with the full NetballSmart Dynamic Warm-Up which can be found under *Resources* when you visit netballnz.co.nz/useful-info/netball-smart

Supplementary Files

Supplementary File S1: Full Secondary Kinetic analysis.

Task	Limb	Metric	Variable	Direction	n	Baseline (Mean +/- SD)	Fatigue (Mean +/- SD)	Change (Delta +/- SD)	95% CI of Change	% Change	Cohen's dz	Effect Magnitude
CMJ	Bilateral	EccPF	CMJ_EccPF	Decrease	15	1350.8 +/- 231.4	1319.3 +/- 214	-31.5 +/- 115.7	-95.6 to 32.5	-2%	-0.27	Small
CMJ	Bilateral	EccBI	CMJ_EccBI	Increase	15	771.8 +/- 197.1	831.1 +/- 102.5	59.3 +/- 191.4	-46.7 to 165.3	13.4%	0.31	Small
CMJ	Bilateral	ConPF	CMJ_ConPF	Increase	15	1384.5 +/- 226.2	1407.3 +/- 203.8	22.8 +/- 111.3	-38.8 to 84.5	2.1%	0.21	Small
CMJ	Bilateral	ConImp	CMJ_ConImp	Decrease	15	323.7 +/- 44.6	305.1 +/- 40.8	-18.7 +/- 21.3	-30.5 to - 6.9	-5.6%	-0.88	Large
CMJ	Bilateral	PeakLF	CMJ_PeakLF	Decrease	15	2360.5 +/- 377.1	2255.7 +/- 384.4	-104.8 +/- 173.9	-201.1 to - 8.5	-4.4%	-0.6	Medium
CMJ	Bilateral	LRFD	CMJ_LRFD	Decrease	15	35669.6 +/- 14531.2	32069.1 +/- 14087.6	-3600.6 +/- 4104.8	-5873.8 to - 1327.4	-9.8%	-0.88	Large
CMJ	Bilateral	LRFD40	CMJ_LRFD40	Decrease	15	17454.8 +/- 10662.4	15967.2 +/- 10954.1	-1487.6 +/- 1514.3	-2326.1 to - 649	-9.2%	-0.98	Large
CMJ	Bilateral	EccLI	CMJ_EccLI	Decrease	15	563.6 +/- 177.9	552.9 +/- 159.4	-10.6 +/- 129.5	-82.3 to 61.1	-0.1%	-0.08	Trivial
SLVJ	L	EccPF	SLVJ_L_EccPF	Decrease	14	1066.7 +/- 163.6	1029.9 +/- 176.3	-36.9 +/- 103.4	-96.6 to 22.9	-3.4%	-0.36	Small
SLVJ	L	EccBI	SLVJ_L_EccBI	Increase	14	821.8 +/- 257.2	822.9 +/- 144.8	1.1 +/- 274.2	-157.2 to 159.4	7.1%	0	Trivial
SLVJ	L	ConPF	SLVJ_L_ConPF	Increase	14	1124.8 +/- 168.6	1147.1 +/- 169.5	22.3 +/- 50.8	-7.1 to 51.6	2%	0.44	Small
SLVJ	L	ConImp	SLVJ_L_ConImp	Decrease	14	307.3 +/- 60.3	284.3 +/- 38.7	-23 +/- 44.5	-48.7 to 2.7	-6.1%	-0.52	Medium
SLVJ	L	PeakLF	SLVJ_L_PeakLF	Decrease	15	1755.2 +/- 252.4	1698.4 +/- 279.3	-56.8 +/- 150.6	-140.2 to 26.6	-3.2%	-0.38	Small
SLVJ	L	LRFD	SLVJ_L_LRFD	Decrease	15	22301 +/- 8434.6	21156.1 +/- 6437.3	-1144.8 +/- 4513.8	-3644.5 to 1354.9	-2%	-0.25	Small
SLVJ	L	LRFD40	SLVJ_L_LRFD40	Decrease	15	11240.2 +/- 6485.5	10110.2 +/- 3311	-1130 +/- 3788	-3227.7 to 967.7	-3.4%	-0.3	Small
SLVJ	L	EccLI	SLVJ_L_EccLI	Increase	15	538.7 +/- 247.2	561.4 +/- 310.5	22.7 +/- 249.5	-115.5 to 160.9	6.6%	0.09	Trivial
SLVJ	R	EccPF	SLVJ_R_EccPF	Decrease	15	1047 +/- 157.9	975.6 +/- 164.6	-71.4 +/- 122.8	-139.4 to - 3.4	-6.5%	-0.58	Medium
SLVJ	R	EccBI	SLVJ_R_EccBI	Decrease	15	845.7 +/- 245.5	774.2 +/- 164.6	-71.5 +/- 266.7	-219.2 to 76.2	-2.4%	-0.27	Small
SLVJ	R	ConPF	SLVJ_R_ConPF	Decrease	15	1117.2 +/- 169.5	1105 +/- 137.2	-12.2 +/- 66.3	-49 to 24.5	-0.6%	-0.18	Trivial
SLVJ	R	ConImp	SLVJ_R_ConImp	Decrease	15	304.7 +/- 53.4	298.6 +/- 47.4	-6 +/- 39.3	-27.8 to 15.8	-1.3%	-0.15	Trivial
SLVJ	R	PeakLF	SLVJ_R_PeakLF	Decrease	15	1671.3 +/- 213.5	1645.4 +/- 195.3	-25.9 +/- 151.4	-109.8 to 58	-1%	-0.17	Trivial

SLVJ	R	LRFD	SLVJ_R_LRFD	Increase	15	20429.9 +/- 8621.2	-21430.6 +/- 10744.3	-1000.7 +/- 6766.5	-2746.4 to 4747.9	6%	0.15	Trivial
SLVJ	R	LRFD40	SLVJ_R_LRFD40	Increase	15	10330.7 +/- 6863.7	-11690.2 +/- 8221.9	-1359.4 +/- 5171.1	-1504.2 to 4223.1	19.4%	0.26	Small
SLVJ	R	EccLI	SLVJ_R_EccLI	Increase	15	572.7 +/- 336.7	625.4 +/- 421.7	52.7 +/- 286.1	-105.8 to 211.1	9.3%	0.18	Trivial
SLDJ	L	EccPF	SLDJ_L_EccPF	Decrease	15	1700.9 +/- 253.5	1581.2 +/- 265.7	-119.6 +/- 152	-203.8 to -35.5	-6.9%	-0.79	Medium
SLDJ	L	EccBI	SLDJ_L_EccBI	Decrease	15	220.2 +/- 43.3	202.5 +/- 42.3	-17.8 +/- 19.5	-28.6 to -6.9	-7.9%	-0.91	Large
SLDJ	L	ConPF	SLDJ_L_ConPF	Decrease	15	1783.5 +/- 164.1	1743.2 +/- 238.3	-40.4 +/- 154.1	-125.7 to 45	-2.4%	-0.26	Small
SLDJ	L	ConImp	SLDJ_L_ConImp	Decrease	15	256.4 +/- 50.5	249.6 +/- 54.8	-6.9 +/- 34.5	-26 to 12.2	-2.3%	-0.2	Trivial
SLDJ	L	JH	SLDJ_L_JH	Decrease	15	0.1 +/- 0	0.1 +/- 0	0 +/- 0	0 to 0	-1.6%	-0.18	Trivial
SLDJ	L	PeakLF	SLDJ_L_PeakLF	Decrease	15	1783.5 +/- 164.1	1743.2 +/- 238.3	-40.4 +/- 154.1	-125.7 to 45	-2.4%	-0.26	Small
SLDJ	L	LRFD	SLDJ_L_LRFD	Increase	15	24617.6 +/- 9223.1	-24684.1 +/- 10183.6	-66.4 +/- 4461.3	-2404.1 to 2537	1%	0.01	Trivial
SLDJ	L	LRFD40	SLDJ_L_LRFD40	Increase	15	12516.8 +/- 7377.4	-12565.9 +/- 7762.8	-49.1 +/- 2462.6	-1314.7 to 1412.8	1.7%	0.02	Trivial
SLDJ	L	EccLI	SLDJ_L_EccLI	Increase	15	427.7 +/- 155	428.3 +/- 272.4	0.6 +/- 218.9	-120.7 to 121.8	0.3%	0	Trivial
SLDJ	R	EccPF	SLDJ_R_EccPF	Decrease	15	1732.6 +/- 190	1596.4 +/- 234.2	-136.1 +/- 195.7	-244.5 to -27.8	-7.6%	-0.7	Medium
SLDJ	R	EccBI	SLDJ_R_EccBI	Decrease	15	224.4 +/- 44.1	202 +/- 41.5	-22.4 +/- 25.3	-36.5 to -8.4	-9.6%	-0.89	Large
SLDJ	R	ConPF	SLDJ_R_ConPF	Increase	15	1361.2 +/- 311.5	1381.3 +/- 247.7	20.1 +/- 164.3	-70.9 to 111.1	3%	0.12	Trivial
SLDJ	R	ConImp	SLDJ_R_ConImp	Decrease	15	258.1 +/- 49.9	247 +/- 45.7	-11.1 +/- 28.8	-27.1 to 4.8	-3.6%	-0.39	Small
SLDJ	R	JH	SLDJ_R_JH	Decrease	15	0.1 +/- 0	0.1 +/- 0	0 +/- 0	0 to 0	-4%	-0.27	Small
SLDJ	R	PeakLF	SLDJ_R_PeakLF	Decrease	15	1745.7 +/- 162.1	1646.7 +/- 218.6	-99 +/- 173.7	-195.2 to -2.8	-5.6%	-0.57	Medium
SLDJ	R	LRFD	SLDJ_R_LRFD	Decrease	15	23129.1 +/- 7966.7	-22678.5 +/- 11021.8	-450.6 +/- 4282.9	-2822.4 to 1921.2	-4.2%	-0.11	Trivial
SLDJ	R	LRFD40	SLDJ_R_LRFD40	Increase	15	11404.5 +/- 6732.8	-11527.4 +/- 7926.1	-122.9 +/- 1982.8	-975.1 to 1220.9	0.4%	0.06	Trivial
SLDJ	R	EccLI	SLDJ_R_EccLI	Increase	15	460.4 +/- 226.1	482 +/- 202.4	21.6 +/- 141.9	-56.9 to 100.2	9.4%	0.15	Trivial
SLHD	L	PeakLF	SLHD_L_PeakLF	Decrease	15	1798.6 +/- 193.7	1736.8 +/- 226.5	-61.8 +/- 198.4	-171.7 to 48.1	-3.1%	-0.31	Small
SLHD	L	LRFD	SLHD_L_LRFD	Increase	15	42204.4 +/- 7815.6	-42886 +/- 7635.5	681.7 +/- 7974.3	-3734.4 to 5097.7	4.1%	0.09	Trivial
SLHD	L	LRFD40	SLHD_L_LRFD40	Increase	15	29805.1 +/- 5775.5	-30378.7 +/- 5621.2	-573.7 +/- 5366.3	-2398.1 to 3545.4	4.2%	0.11	Trivial
SLHD	L	EccLI	SLHD_L_EccLI	Increase	15	475.7 +/- 209.3	494.2 +/- 287.5	18.5 +/- 156	-67.9 to 104.9	3.2%	0.12	Trivial
SLHD	R	PeakLF	SLHD_R_PeakLF	Decrease	15	1817.4 +/- 195.8	1782.9 +/- 157.5	-34.4 +/- 142.7	-113.5 to 44.6	-1.4%	-0.24	Small

SLHD	R	LRFD	SLHD_R_LRFD	Decrease	15	41391.4 +/- 7639	-41053.6 +/- 7526.1	-337.8 +/- 7071.3	-4253.7 to 3578.2	0.6%	-0.05	Trivial
SLHD	R	LRFD40	SLHD_R_LRFD40	Decrease	15	29018.4 +/- 5338	-28014.7 +/- 6479.8	-1003.6 +/- 5205.1	-3886.1 to 1878.8	-2.7%	-0.19	Trivial
SLHD	R	EccLI	SLHD_R_EccLI	Decrease	15	482.1 +/- 241.1	470 +/- 281.7	-12.1 +/- 241.5	-145.8 to 121.6	3%	-0.05	Trivial