Predicting Secondary Injury Risk Following Anterior Cruciate Ligament Reconstruction:

A Literature Review

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A capstone project submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements for the degree of

MASTER OF PHYSICIAN ASSISTANT STUDIES

Department of Physician Assistant Studies

Max Rady College of Medicine and Faculty of Graduate Studies

University of Manitoba

Winnipeg, Canada

May 15, 2021

Abstract
Background: The anterior cruciate ligament (ACL) is the most commonly ruptured knee ligament. Surgical reconstruction offers the best prognosis for recovery by increasing stability and decreasing complications. Unfortunately, after an athlete resumes activity, there is an increased risk of injury to both the graft, and the contralateral ACL. Previous studies have investigated return to sport (RTS) assessment tools' capability to foresee secondary ACL injury, largely providing no concrete evidence as to which tools are predictive of secondary ACL injury.
Objective: This study aimed to evaluate existing RTS assessment tools' capability of predicting a secondary ACL injury in athletes who RTS. This study sought to identify tools that orthopedic surgeons and physician assistants could utilize to aid clinical decision making when considering RTS following surgical reconstruction.
Methods: This literature review searched the PubMed database from 2015-present, using search terms related to ACL reconstruction and RTS. All abstracts were screened against inclusion criteria. The primary outcome measured was RTS tools' capability to predict secondary ACL injury.
Results: Five articles met the selection criteria. Two studies concluded that passing RTS criteria did not significantly decrease the risk of secondary ACL injury. Two studies indicated that available literature was insufficient to confidently determine the predictive validity of RTS for secondary ACL injury. Only one study found an association between passing RTS criteria and reduced secondary ACL risk; functional, psychologic, and radiologic tests were identified to have capability in predicting secondary ACL injury. This data was used to create an evidence-based RTS battery consisting of tests, cut-off points and predictive capability of secondary ACL injury.
Conclusion: Based on the heterogeneity of the results, there is a need for more research to determine the best RTS battery and the associated predictive capability for secondary ACL injury. A preliminary evidence-based RTS battery incorporating functional, psychological, and radiological measures was proposed; large scale studies are required to validate this tool.

Terminology:

- **Knee reinjury:** Any secondary knee injury involving injury to the ligaments, graft, menisci or cartilage. Any knee injury involving patellar subluxation or dislocation.
- **Secondary ACL injury**: Graft rupture or contralateral ACL injury.
- **Graft rupture/failure/injury**: Injury to the surgical ACL graft.
- **Contralateral ACL rupture/injury**: Injury to the naïve ACL, contralateral to the surgical graft.

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Introduction

Epidemiology of ACL tear

The anterior cruciate ligament (ACL) is an important stabilizing ligament of the knee, serving to resist the combined motions of anterior tibial translation and internal rotation.[1] The ACL is the most commonly injured knee ligament, with an annual tear rate of approximately one in 3,500.[2,3] Rates are higher in populations that engage in activities involving sudden changes in movement, rapid deceleration, jumping, and blows to the lateral knee. The annual incidence of ACL tears in athletic populations is between 1.3% to 1.7%, with lifetime rupture rates of one in 29 (3.5%), and one in 50 (2.0%) for female and male athletes, respectively.[4-6] Nearly half (49.5%) of all ACL injuries occur in a non-contact situation with the athlete's lower limb positioned a knee-in and toe-out position, suggesting that dynamic knee valgus force is a high-risk action for ACL injury.[2,7] Other high-risk positions for ACL injury include knee-out and toe-in, and knee hyperextension.[2,7] ACL injuries most often occur in competition (49.2%), followed by practice (34.8%), and leisure activities (8.5%).[8]

Surgical Reconstruction

ACL tears typically result in knee instability, thus 74% of patients will ultimately undergo surgical reconstruction, which is regarded as the gold standard of care for skeletally mature individuals.[9,10] The decision to pursue anterior cruciate ligament reconstruction (ACLR) is guided by clinical practice guidelines, which consider functional instability, age, professional and sports exposure, time from injury, laxity, associated meniscus and/or cartilage lesions, and social and occupational expectations.[9] Non-surgical management includes physical therapy, bracing and activity modification.[11] ACLR offers lower rates of subsequent medial meniscal injury and clinically significant knee instability than patients managed non-operatively.[12] Furthermore, ACLR offers the best prognosis for recovery from an ACL injury, with nearly half of young athletes successfully completing rehabilitation and returning to full activity within 12 months; two-thirds return to full activity within two years.[13,14]

Epidemiology of Secondary ACL Injury following ACLR

Unfortunately, even with rehabilitation, secondary ACL injury occurs in 15-17.9% of athletes within two years post-ACLR, with high tear rates to both the ipsilateral (7-9.2%) and contralateral (8-8.7%) ACL.[9,15]

Athletes younger than 25 years who return to sport (RTS) have a higher reinjury rate of 23%.[15] This may be driven by a mismatch between RTS rates and functional readiness.[16] Return to knee strenuous (level I) sports (involving pivoting, cutting, jumping) within the first post-operative year is independently associated with six times higher secondary ACL injury rates.[16] Athletes under 25 were more likely to return to level I sports in the first post-operative year than athletes older than 25 (RTS rates of 60.4% and 28.0%, respectively), despite lower RTS criteria pass rates among those who return to high level sports in the first postoperative year (38.1% of younger, and 59.1% of older athletes passed RTS criteria).[16]

Readiness to RTS

Historically, RTS decisions have been based on time, an easily measured value and an excellent predictor of graft maturity. Post-ACLR serial T2-weighted magnetic resonance imaging (MRI) has shown autograft density stabilization between nine to 12 months, indicative of graft maturation.[17] These imaging findings are supported by the seven-fold increased rate of secondary ACL injury in athletes who return to level I sports within nine months of ACLR.[18-20] While time is a reliable predictor of graft maturation, readiness encompasses psychological and functional factors, which require separate assessment as these factors may independently influence secondary ACL injury risk.[21]

Clinicians and researchers tend to rely heavily on time to the exclusion of other factors; post-operative time was considered in 85% of RTS decisions, and used as the sole criterion in 42% of decisions.[21] Other criteria commonly considered in studies include strength and clinical examinations, which were considered in 41% and 26% of studies, respectively. Researchers have ignored performance-based criteria, hop tests, and self-reported readiness, which were considered in only 20%, 15%, and 12% of studies, respectively.[21] Success on functional RTS tests (e.g., hop tests, strength, movement analysis) is independently associated with a 92% reduced rate of secondary ACL injury.[16] The most commonly used functional test scoring system is the Limb Symmetry Index (LSI), which compares bilateral lower limb strength and hop tests at six months post-ACLR (Figure 1, Appendix).[22]

Fear of re-injury best explain hesitancy to RTS as indicated by 78% of ACLR patients.[23] Recent literature demonstrates that self-report measures of psychological readiness has little or no relationship with athletes' strength and power measures, suggesting that physical recovery and psychological recovery are separate constructs. Pairing these two constructs may better serve as a tool to identify athletes who are not ready for RTS than either measure used alone.[24] When used at six months post-ACLR, single leg hop LSI in conjunction with the ACL-Return to Sport after Injury (ACL-RSI) self-report tool identified 91% of athletes who did not reach their pre-injury activity level at 12 months post-ACLR.[23] Unfortunately, clinicians rarely consider this measure when evaluating an athlete's readiness to RTS.[21]

Factors contributing to inadequate RTS decisions

Current recommendations for assessment following ACLR suggest 'a battery of tests mimicking the reactive elements and the decision-making steps athletes use in real sport situation, measuring various components of physical performance (e.g., change of direction ability, muscular strength, hop tests) and psychosocial readiness assessments.'[14] The ambiguity of this definition combined with the comprehensiveness of testing necessitates RTS batteries to be administered and interpreted by specialized practitioners.[14] Due to systemic constraints, orthopedic surgeons, sports medicine physicians, and physician assistants (PAs) rarely have the time, space, or equipment to complete comprehensive RTS assessments.[25] Furthermore, rehabilitation is not covered within the public health system, restricting over one-third of Canada's population who are not covered by private health insurance, from consulting with physiotherapists.[26] With this in mind, pressure from eager patients combined with the lack of RTS guidelines may provoke clinicians to prematurely encourage RTS, putting patients at risk of secondary injury.

Objective

Interest in simple measures of the aspects of human movement has increased as these represent a time- and cost-effective method to gain insight into patient readiness to RTS. Important features of RTS tools include the ability to assess whether patients have returned to their previous level of functioning, to predict the risk of subsequent ACL injury and the capability of being completed within the confines of the system the practitioner works within. The identification of the most clinically useful tools may assist physicians and PAs to confidently advise decisions regarding RTS to patients following ACLR and are unwilling or unable to attend rehabilitation. The objective of this review is to evaluate existing RTS assessment tools' capability of predicting secondary ACL injury in athletes who RTS.

Methods

Search Strategy

A literature review addressing the use of RTS tools to predict secondary ACL injury was conducted using the PubMed database on December 1, 2020. Three hundred and eight studies were identified using search terms 'Anterior Cruciate Ligament/ACL,' 'Return to sport/RTS,' 'Assess/Tool/Test,' and 'injury/reinjury.' The search was narrowed to include meta-analyses and systematic reviews published in English from 2015-Current; seventeen studies were identified.

All abstracts were screened by one author against the following inclusion criteria: (1) main focus was to evaluate subsequent ACL injury after ACLR; (2) studies involved participants who have underwent ACLR with any graft type; (3) RTS battery was utilized; (4) results of RTS battery testing was reported; (5) subsequent injury rates were reported for a two year follow-up period. Full-text studies were retrieved if the abstract provided insufficient information to establish eligibility or if the study passed initial eligibility screening.

Five studies were identified to be included in the review; all of which followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses reporting standards. The study selection process is detailed in Figure 2 (Appendix).

Results

1. One in 5 Athletes Sustain Reinjury Upon Return to High-Risk Sports After ACL Reconstruction: A Systematic Review in 1239 Athletes Younger Than 20 Years[27]

Barber-Westin and Noyes[27] aimed to determine RTS rates, the effect of participation in high-risk sports, sex, and graft type on ACL reinjury rates, and whether objective criteria before RTS correlate with reinjury rates.

Methods: Two databases were searched for key terms related to ACLR. Articles had to include patients younger than 20 years undergoing transphyseal ACLR with a mean post-operative follow-up of two years, and report RTS pass rates and reinjury rates. After screening, eight original research articles (1,239 participants) were chosen. Table 1 (Appendix) provides search methodology, including databases, search terms, and inclusion criteria.

Outcomes: 87% of athletes returned to sport, with 80% returning to high-risk activities. Secondary ACL injury occurred in 18% of patients, including bilateral ACL tears in 2% of patients. The mechanism of reinjury (contact, non-contact) was only reported in 10% of graft ruptures, and 0% of contralateral ACL injuries.

Graft failure was reported in 10% of patients, with 90% of failures occurring during high-risk sports. Table 2 (Appendix) describes differences in graft failure rates with regards to sex and autograft selection. Contralateral ACL failure was reported in 10% of patients, with 80% occurring during high-risk sports with no significant sex difference identified.

Correlation of objective testing and discharge criteria before RTS and reinjury rate could not be established as only two studies cited any objective criteria for RTS (Table 2, Appendix). Conclusions regarding the effect of resuming high-risk sports compared with low-risk activities on reinjury rate could not be made. It was concluded that knee stability, strength, neuromuscular control, agility, and psychological measures before RTS remains paramount in young athletes.

Strengths: Extensive research (including 107 references) led to the publication of a holistic systematic review with a large sample size (1,239 participants). The authors included a variety of tables and figures to assist the reader with data interpretation related to patient demographics, RTS criteria, RTS data, and reinjury data. Finally, the graft reinjury and contralateral injury rates aligned with previous research.[9,15]

Limitations: This study limited generalizability and reduced external validity by restricting the population to only include individuals younger than 20 years old. Additional limitations include low evidence levels (fair or poor as measured by a modified Coleman score) in seven of the eight studies, the potential for unrecognized ACL failures (not all studies conducted clinical examinations), and the inability to determine the mechanism of re-injury.

2. The Association Between Passing Return-to-Sport Criteria and Second Anterior Cruciate Ligament Injury Risk: A Systematic Review With Meta-analysis[28]

Losciale, Zdeb, Ledbetter, Reiman and Sell[28] evaluated whether criteria-based RTS decisions were associated secondary ACL injury. Additional aims are described in Table 2 (Appendix).

Methods: Six databases were searched for key terms related to ACLR. Articles had to include patients recovering from ACLR (any graft type) with the study population's average age between 10-50 years old. Furthermore, objective RTS criteria needed to be used, with RTS pass rates and subsequent ACL injury rates reported. After screening, four original articles (576 participants) were included. Table 1 (Appendix) provides search methodology, including databases, search terms, and inclusion criteria.

Outcomes: Overall, 42.7% (95% Confidence Interval [CI]: 18, 69%) of patients passed RTS criteria, and 14.4% (95% CI: 8, 21%) of those who passed criteria experienced a second ACL injury, compared to 15.6% (95% CI: 6, 29%) of those who failed.

Passing RTS criteria did not decrease risk of reinjury (Risk Difference [RD] -3%, 95% CI:-16, 10%; I^2=74%, p=0.610), graft injury (RD -7%; 95% CI: N/A; I^2=74%; p=.140) or contralateral injury (RD 4%; 95% CI: N/A; I^2=28%; p=.160)

This study concluded that the evidence did not show an RD between passing RTS criteria and risk of secondary ACL injury. Additional research is required to determine RTS criteria capable of predicting secondary ACL injury.

Strengths: This meta-analysis confirmed a need for improved prognostic capability of RTS testing. Ambiguous terms such as positive (failing) test and negative (passing) test were clearly defined, ensuring uniform interpretation by all readers. Numerous tables and figures helped readers interpret data regarding study characteristics, RTS criteria components included in each study, RTS rates, and secondary injury data.

Limitations: This study is limited by clinical diversity between studies, including variable RTS definitions and follow-up periods, differing levels of competition among the participants, and demographic diversity.

3. What is the Evidence for and Validity of Return-to-Sport Testing after Anterior Cruciate Ligament Reconstruction Surgery? A Systematic Review and Meta-Analysis[29]

Webster and Hewett[29] evaluated the proportion of patients who passed RTS test batteries after ACLR and whether passing RTS batteries increased the rates of RTS and reduced rates of secondary knee and ACL injury.

Methods: Five databases were searched for key terms related to ACLR; additionally, eight articles were hand-searched from 'articles in press' lists of sports medicine journals, and the references of included studies. Articles had to include patients who had undergone ACLR (primary or revision), have utilized an RTS battery with multiple domains (strength, hop, function), and report RTS pass rates. After screening, 18 original articles (2,000 participants) were included in the review, with 16 included in a meta-analyses; two studies were not included due to data overlap. Table 1 (Appendix) provides search methodology, including databases, search terms, and inclusion criteria.

Outcomes: The most common RTS tests were hop tests (18 of 18 studies) and quadriceps strength (17 of 18 studies). Only five studies examined post-RTS injury, with three of the five incorporating a minimum two year follow-up.

Passing an RTS battery demonstrated a non-statistically significant risk reduction (RR) of nonspecific knee injuries (RR 0.28, 95% CI:0.04, 0.94; p=0.09, I^2=13%), but had little effect on subsequent ACL injuries (RR 0.80, 95% CI: 0.27, 2.3l p=0.7; I^2=79%). Passing an RTS battery decreased risk of graft rupture by 60% (RR 0.40, 95% CI:0.23, 0.69, p<0.001), but resulted in a 235% increased risk of contralateral ACL injury (RR 3.35; 95% CI:1.52, 7.37; p=0.003; I^2=0%). Unfortunately, the included studies used different RTS batteries and passing criteria (Table 2, Appendix), thus the identification of a predictive test could not be determined. Table 3

(Appendix) provides injury rates and additional results including RTS pass rates, and correlations between passing an RTS battery and RTS rates and achieving pre-injury Tegner score.

Additionally, the 'penalty' of multiple tests in large test batteries was identified as a concern. Batteries typically include tests across several domains, requiring a score (often 90% LSI) to pass each test. Thus, if an athlete passes the first test, and a second test is added, the percentage of athletes who pass will be lower. This is more pronounced in batteries with many tests; for example, if 80% of athletes pass each test of a test battery, then only 64% (0.8^2) would pass a 2-test battery, 51% (0.8^3) for a 3-test battery, and so on.[29]

In summary, this review demonstrated that RTS test batteries have limited validity in the reduction of subsequent ACL injury risk but not that they have no benefit. Quantitative and qualitative feedback may offer patients insight into their rehabilitation process, which can boost patient confidence and compliance; conversely, disappointing feedback may decrease confidence. The 'penalty' of multiple tests should be considered when administering and interpreting the results of test batteries.

Strengths: Performing a meta-analysis enabled the writers to quantitively assess the results of previous research for RTS criteria pass rates, and the correlation between passing RTS criteria and subsequent knee injuries (Table 3, Appendix). Finally, the inclusion criteria were broad in terms of age, sports played, and graft type, which enabled the population to be represented holistically.

Limitations: First, the definition of RTS varied across studies examined, making it difficult to compare data. This phenomenon prompted a response by Capin, Snyder-Mackler, Risberg and Grindem[30] to evaluate the methodology and re-compute data after omitting distorting studies, yielding much different results. Secondly, no study reported on exposure, making it unclear if secondary injury was associated with higher exposure to risky situations. Thirdly, there was an error in the publication, stating that 17 papers were included in the meta-analysis; e-mail discussion with the author clarified that 16 papers were included. Finally, though broad inclusion criteria were identified as a strength, it is also a limitation as variables such as age, sport type and graft type may have confounded the data.

4. Return to Sport Tests' Prognostic Value for Reinjury Risk after Anterior Cruciate Ligament Reconstruction: A Systematic Review[31]

Ashigbi, Banzer, and Niederer[31] reviewed the literature on RTS functional tests and self-reported function, and provided an overview of evidence based RTS considering ACL injury risk.

Methods: Four databases were searched for terms related to ACLR; additionally, 13 unpublished and gray literature were retrieved from www.guidelines.gov, www.opengrey.eu, www.clinicaltrials.com and www.controlled-trials.com. Studies had to include male and female adolescents and adults involved in sports, who experienced ACLR and rehabilitation for a primary unilateral ACL rupture. After screening, eight prospective cohort studies (6,140 participants) were included. Table 1 (Appendix) provides search methodology, including databases, search terms, and inclusion criteria.

Outcomes: Reinjury rates (combined ipsilateral and contralateral injuries) ranged from 1.5% to 37.5%. Return to level 1 sports led to 4.32 times higher reinjury rates over two years (p=0.048).

Objective criteria were only cited in 10-13% of literature reviewed. Strength and the four hop tests (single, cross over, triple, 6-m timed) were the most commonly cited tests, with LSI ≥

90% as the common cut-off. LSIs may overestimate knee function, potentially putting an athlete at risk for a second ACL injury. Estimated pre-injury capacity (EPIC), a measure comparing the postoperative function of the injured leg with the pre-operative function of the uninjured leg (Figure 1, Appendix) was more sensitive in predicting second ACL injuries than LSI (EPIC: sensitivity: 0.818, 95% CI: 0.523-0.949; LSI: sensitivity: 0.273, 95% CI: 0.010-0.566).[22]

Three measures were found to be associated with an increased risk of graft rupture. First, failure to meet cutoffs on 1+ criteria (Table 2*[A-F], Appendix) before RTS was associated with four times the risk of graft rupture (Hazard Ratio [HR] 4.1, 95% CI: 1.9, 9.2; $p \leq 0.001$). Second, every 10% decrease in isokinetic (60°/s) hamstrings to quadriceps (HQ) strength ratio was independently associated with 10 times the risk of graft rupture (HR 10.6 per 10% difference, 95% CI: 10.2, 11; $p=0.005$). Finally, scoring ≥ 19 points on the Tampa Scale of Kinesiophobia (TSK-11) self-report questionnaire correlated with 13 times greater risk of graft rupture within 24 months post-ACLR (RR 13.0; 95% CI: 2.1–81.0; $p=0.03$).

Two studies found that radiological measures of posterior tibial slope (PTS) could predict secondary ACL rupture. Both studies identified that mean PTS was higher in patients who experienced secondary ACL injury compared with patients who did not.[32,33] PTS ≥ 12° was associated with a 59% incidence of secondary ACL injury ($p=0.001$); Post-hoc analysis of Webb, Salmon, Leclerc, Pinczewski and Roe[33] demonstrated PTS ≥ 12° was associated with a 150% increased risk of secondary ACL injury (RR 2.54; 95% CI 1.6, 4.0; $p<0.0001$).[32,33]

Finally, three-dimensional (3D) motion analysis during drop vertical jump (DVJ) and standing postural stability were used to identify a set of four variables predictive of secondary ACL injury (C: 0.94; Sensitivity: 0.92; Specificity 0.88); Table 4 (Appendix) describes the variables identified and provides associated statistics. Additionally, hip rotation moment independently predicted ACL injury (C = 0.81; sensitivity = 0.77; specificity = 0.81); cut-off values are described in Table 4 (Appendix).[34]

Ashigbi et al.[31] concluded that neuromuscular function (quadriceps strength, hop tests), self-reported fear (TSK-11), and biomechanical measures of DVJ may be used to assess the risk for re-injury after ACLR.

Strengths: The use of English and German papers enabled a broader breadth of knowledge to be uncovered. The study examined radiologic, clinical, functional, and psychological factors that could potentially be involved in RTS.

Limitations: The studies in this paper came from multiple sources (national registry, single surgeon, cohort study), with varying surgical techniques, and an array of health professionals involved, all of which could potentially confound the data. Statistical relationships were described vaguely, obliging readers to search for statistics within the cited papers. Finally, most of the functional tests were combined with other RTS tests, making it difficult to determine individual RTS test correlation with reinjury risk.

5. Hop Testing Lacks Strong Association With Key Outcome Variables After Primary Anterior Cruciate Ligament Reconstruction: A Systematic Review[35]

Losciale, et al.[35] evaluated the strength of association between hop testing and RTS, knee reinjury, subjective report of knee function, and post-traumatic osteoarthritis (PTOA) after primary ACLR. A secondary goal of this study was to determine whether hop testing could predict a favourable result on the same outcomes.

Methods: Six databases were searched for terms related to ACLR. Studies had to include patients with any ACLR graft type attempting to RTS, with study population ages ranging between 10-50 years old. Furthermore, the hop test procedure must be described, and include objective performance data and a statistically measured association between hop testing and a primary outcome variable (self-report of knee function, return to preinjury level of activity, presence of reinjury, or present of PTOA). After screening, 21 cohort, case-control, or case series articles (4,476 participants) were included in the study. Table 1 (Appendix) provides search methodology, including databases, search terms, and inclusion criteria.

Outcomes: The most commonly associated measure with hop testing was the IKDC score (6 studies, 344 patients). This tool appeared to be most useful when hop testing was performed between 6-17 months after ACLR (r=0.20 to 0.60). The knee injury and osteoarthritis outcome score (KOOS) was also associated with hop testing (4 studies, 262 participants, r= -0.10 to 0.62).

Two studies (264 participants) examined the relationship between hop testing (passing score: LSI ≥ 90%) and knee reinjury with no meaningful association identified. It was concluded that hop testing alone is not a sufficient predictor of a second knee injury after ACLR.

Two studies (232 participants) examined the relationship between hop testing and secondary ACL injury. One study (74 patients) found that LSI>90% on the 6-m timed hop at six months post-ACLR was associated with a 3% RR of subsequent graft or ACL injury over the 2-year follow-up (95% CI: 0.93-1.02; p=.20). All other hop tests (single-hop for distance, triple hop, crossover hop) were not associated with risk-reduction of subsequent ACL injury.[20] The second study (158 patients) found no statistically significant differences between hop-test scores and graft injury.[36] It was concluded that predictive validity of hop tests for secondary ACL injury cannot be established based on available literature. A battery incorporating hop testing, measures of thigh strength, proprioception and patient subjective report of knee function is required to make evidence informed RTS decisions.

The study also found that preoperative hop LSI ≤ 75% was associated with 2.9x greater risk for PTOA development within 10 years post-ACLR (95% CI: 1.2, 7.1; p=0.02).

Strengths: This review's strengths include the use of 21 studies (4,476 patients), and two independent screeners to select relevant articles. The study included clear inclusion and exclusion criteria, thus could be replicated.

Limitations: The limitations include only selecting English language peer-reviewed articles, which potentially reduced the body of knowledge available and excluding new theses not yet reviewed. Keeping the date range broad may have led to variations in technique across the years and decreased the focus from current data. The review had originally sought to perform a meta-analysis, but the non-uniformity of studies selected eliminated the possibility of statistical pooling.

Discussion

It is clear that there is ambiguity surrounding the capability of RTS tools to predict secondary ACL injury in athletes who RTS. Of the five articles reviewed, only one study identified predictive validity of some RTS tools, while two studies indicated that passing RTS criteria did not significantly reduce risk of secondary ACL injury, and two studies noted insufficient evidence to determine predictive capability of RTS tools.

Ashigbi et al.[31] identified predictive validity of RTS tools including functional, self-report radiological, 3D-Motion Analysis measures. Functionally, EPIC < 90% on strength and hop tests could predict secondary ACL injuries (sensitivity: 0.818; 95% CI: 0.523-0.949) with greater sensitivity than LSI < 90% (sensitivity: 0.273; 95% CI:0.010, 0.566).[31] Every 10% decrease in isokinetic (60°/s) HQ ratio was independently associated with 10 times greater risk of graft rupture (HR 10.6 per 10% difference, 95% CI: 10.2, 11; p=0.005). Furthermore, failure of isokinetic HQ ratio, single hop, 6-m timed hop, triple hop, triple crossover hip, on-field sport-specific rehabilitation (OFSSR) or T-Test was associated with four times greater risk of graft rupture (HR 4.1, 95% CI: 1.9, 9.2; p≤0.001); passing criteria is listed in Table 2*[A-F], Appendix. Psychologically, high self-reported fear (TSK-11 ≥ 19) at RTS corresponded with higher risk of graft rupture (RR 13.0; 95% CI: 2.1, 81.0; p=0.03).[31] The association between self-report and subsequent graft rupture suggests that fear and perceived disability affects performance and may contribute to injury. Radiologically, PTS ≥ 12° was associated with 150% increased risk of secondary ACL injury (RR 2.54; 95% CI 1.6, 4.0; p<0.0001), suggesting that anatomical factors contribute to reinjury risk. Finally, 3D analysis during DVJ and standing postural stability identified four variables predictive of secondary ACL injury (C = 0.81; sensitivity = 0.77; specificity = 0.81).

Two studies had insufficient evidence to determine the predictive validity of RTS for secondary ACL injury but suggested that a battery incorporating hop testing, strength measures, proprioception, and subjective report of function is required to make informed RTS decisions.[27,35]

Two studies indicated that passing RTS criteria did not decrease the risk of secondary ACL injury, but were able to identify isolated graft and contralateral ACL injury risks.[28,29] Webster and Hewett[29] identified that passing an RTS battery led to a 60% reduction in graft rupture risk (p < 0.001), and a 235% increased risk of contralateral ACL rupture (p=0.003). Losciale et al.[28] identified similar nonsignificant trends, with passing RTS criteria associated with a 7% decreased risk of graft injury (p=.140) and 4% increased risk of contralateral ACL injury (p=0.160). These results suggest athletes who passed an RTS battery may have disregarded their contralateral knee throughout the rehabilitation process. This emphasizes the importance of rehabilitation and assessment of both knees before permitting an athlete to RTS following ACLR.

Incidental Findings

Webster and Hewett[29] received critique by Capin et al.,[30] who had apprehensions about the study methodology. There was concern that pooling studies with substantial clinical and methodological diversity caused data skewing. Specifically, two studies were thought to have distorted data by involving young patients with premature RTS to high level sports.[22,37] By omitting the distorting studies, statistically significant reduced risks of secondary ACL injury (RR 0.30; 95% CI: 46, 88%; p <0.01) and secondary graft rupture were computed (RR 0.22; 95% CI: 0.10, 0.48; p=0.003). Insufficient data prohibited computation of secondary contralateral ACL injury risk (Table 5). It was concluded that athletes who pass RTS test batteries have a lower risk of any knee re-injury, any second ACL injury, and ACL graft rupture. No conclusions could be made regarding secondary contralateral ACL injury risk. Capin et al.'s[30] response demonstrates the importance of study selection when conducting a meta-analysis.

Table 5: Comparison of data from Webster and Hewett[29], and Capin et al.[30]

Passing RTS battery's associated risk of:	Webster and Hewett[29]	Capin et al[30]
Any subsequent knee injury	**72% lower risk**[20,38] (RR 0.28; 95% CI: 0.04-0.94; p=0.09; I^2=13%)	
Secondary ACL injury (graft or contralateral ACL)	**20% lower risk**[20,22,36-38] (RR 0.80, 95% CI: 0.27, 2.3; p=0.7)	**75% lower risk**[20,36,38] (RR 0.30; 95% CI: 46, 88%; p <0.01)
Secondary graft rupture	**60% lower risk**[20,22,36-38] (RR 0.40; 95% CI: 0.23, 0.69; p < 0.001)	**78% lower risk**[20,36,38] (RR 0.22; 95% CI: 0.10, 0.48; p=0.003)
Secondary contralateral ACL injury	**235% increased risk**[20,22,37,38] (RR 3.35; 95% CI: 1.52 ,7.37; p=0.003)	**Insufficient data to compute statistics**[20,36,38] 3 injuries among pass group (171 patients) 1 injury among fail group (101 patients)

Losciale et al.[39] directed readers toward to a case-control and cohort study (114 participants) by Paterno, Huang, Thomas, Hewett, and Schmitt[39] that generated factors putting individuals at five times greater risk of secondary ACL injury within 24 months (OR 5.14; 95% CI:1.00, 26.46; sensitivity 66.7%; specificity 72.0%). Two risk profiles related to high risk of ACL injury were identified: (1) age <19 years, triple hop for distance between 1.34 and 1.90 times body height with LSI <98.5%, or (2) age <19 years, triple hop for a distance > 1.34 times body height with LSI >98.5%, female sex, and high knee-related confidence, as measured by Question 3 of the KOOS-Quality of Life (KOOS-QoL) survey.[39] Future studies should continue to examine the validity of concepts using a larger sample size with varying demographics.

Clinical Implications

Despite low RTS pass rates (range 23-43%), high rates of athletes returned to sport (range 46-87%), with secondary ACL injury rates between 14-18% following RTS.[27,28] These statistics are concerning as many athletes may experience subsequent knee injuries by returning to sport without acceptable knee function and control. Health care practitioners should emphasize the importance of rehabilitation and be firm when advising an athlete refrain from competing.

Unfortunately, current RTS criteria do not appear to predict subsequent ACL injury.[29] Determining optimal RTS criteria will minimize the number of premature clearance decisions, and reduce secondary ACL injuries due to premature RTS. The need for testing and documentation of knee stability, strength, neuromuscular control, agility, and psychological measure before RTS remains paramount, with prospects of identifying a tool to reliably predict the risk of secondary ACL injuries.[27] Healthcare practitioners should strive to holistically evaluate risk of secondary knee injury with a battery of tests, incorporating functional, psychological, and radiological measures, although the 'penalty' of multiple tests should also be considered.[29] Health practitioners could mitigate this penalty by distributing tests across multiple sessions in an attempt to provide a more accurate representation of performance. Table 6 suggests a preliminary evidence-based RTS battery that is accessible for most patients and offers high predictive capability. This battery is intended for use at nine months post-ACLR, in accordance with previous research.[18,19,20]

Table 6: Evidence Based RTS after ACLR Battery for Clinician use at 9 months Post-ACLR

Category	Test	Passing Cut-off	Test failure increases risk of:	Statistics
Functional	Hop (single, crossover, triple hop for distance; 6-meter timed) and Isometric Quadriceps Strength* (90° knee flexion)	EPIC ≥ 90%**	Secondary ACL injury	Sensitivity: 0.818; 95% CI: 0.523, 0.949[22,31]
Psychological	TSK-11***	< 19 points	Graft Rupture	RR 13.0; 95% CI: 2.1, 81.0; p=0.03[31]
Radiologic	Knee X-Ray	PTS < 12°****	Secondary ACL injury	RR 2.54; 95% CI 1.6, 4.0; p<0.0001[31,33]

*Quadriceps Strength requires access to an electromechanical dynamometer.
**In absence of pre-operative hop and strength testing of the uninjured leg, population specific (e.g., age, sport) data if pre-operative measures are unavailable.
***The ACL-RSI has also demonstrated promise in predicting confidence in movement and likelihood of RTS, however the data correlating ACL-RSI score and re-injury is currently lacking; if this data emerges, the ACL-RSI may serve as a suitable alternative to the TSK-11.[40]
****Unfortunately, there is low likelihood of revision surgery to adjust PTS, thus, athletes with PTS ≥ 12° should be informed of the associated risk of secondary ACL injury.
Note: OFSSR, T-Test, HQ ratio, 3D analysis during DVJ and standing postural stability may have predictive capability but were not included in this battery due to the requirement of specialized equipment and skills for test administration and result interpretation.

Limitations

The inclusion criteria were strict in terms of article type, publication date, and language. These restrictions promoted obtention of current high-quality evidence but came at a cost of failure to include the latest unfiltered evidence. Only five articles met inclusion criteria, making it difficult to draw conclusions supported by data. Accessing only one database may have neglected relevant articles that could be found in other databases.

A second limitation from this literature review is the lack of research available with clear definitions of RTS and a documented use of an RTS battery using objective pass criteria. All five studies encountered unclear and non-objective RTS criteria, disabling authors from performing high quality meta-analyses.[27-29,31,35] When objective data was compiled, it was derived from a variety of different RTS tests with differing pass criteria, thus, included multiple confounds and often demonstrated high heterogeneity. Future studies should include clear RTS definitions (as described by Arden et al.'s consensus statement) and objective criteria, so optimal objective RTS criteria can be discovered analyzed via meta-analysis.[14]

Thirdly, the literature review process revealed that studies incorporating psychological factors of RTS following ACLR have not been extensively assessed by systematic reviews; only one included review documented an association with self-report psychological measures and ACL injury rates.[31] Future studies should include self-report tools as part of their RTS battery, to further investigate psychological readiness's predictive value for secondary ACL injury.

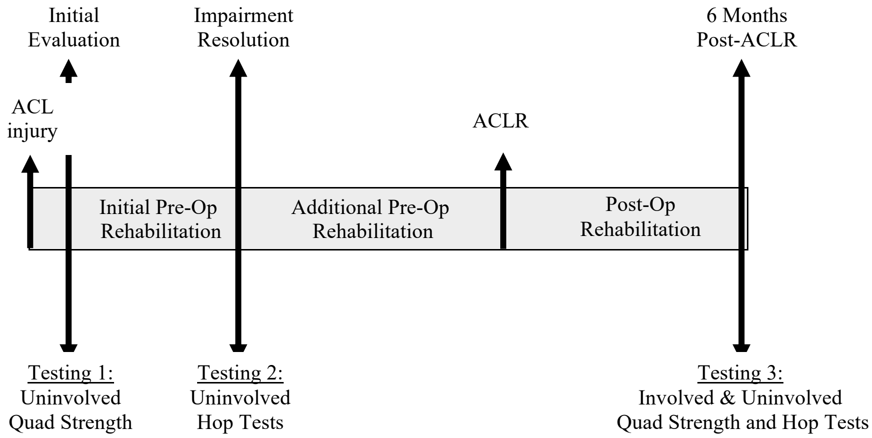
Finally, due to the variation and unpredictability of human movement combined with limitless lifestyle confounds, it is difficult to perform a randomized control study. Furthermore, it is unethical to conduct a study in which it is believed that a specific group may be at higher risk of injury. Furthermore, it is impossible to control the inciting event and the participant's movement strategy at the time of injury. Thus, diligent, objective documentation of RTS tools (including cut-offs), participant results, and subsequent injury rates performed by qualified practitioners is imperative for the success of future analyses.

Conclusion

ACL injuries are complex phenomena resulting from an interconnected web of risk factors including demographics (age, sex), psychologic factors (anxiety, attention, fatigue), training load, movement strategy, and unanticipated environmental events. Clinicians should strive to understand interactions between risk factors to mitigate ACL injury risk and improve assessment methodologies.[41]

Additional research is required to determine the premier RTS battery, and its associated predictive capability of secondary ACL injury. At this time, hop and isometric quadriceps strength (EPIC ≥ 90%), TSK-11 (< 19 points), knee X-Rays (PTS < 12°) have evidence in predicting secondary ACL injury. This battery of evidence-based tests requires minimal equipment and space, and results are easily interpreted to provide high predictive capability, thus, is suitable for use by orthopedic physicians, sports medicine physicians, PAs, and physiotherapists. Future research should assess this battery with large sample sizes of varying demographics. Pre-season performance assessments using a similar battery may also serve as a valuable tool for both risk reduction and retrospective analysis of ACL injury. Orthopedic practitioners should be diligent in the documentation of RTS tools used (including cut-offs), participant results of RTS battery, and subsequent injury rates to enable future researchers to conduct valid retrospective analyses.

Appendix



Quad Strength LSI:

$$\frac{\text{Involved (6 months)}}{\text{Uninvolved (6 months)}} \times 100$$

Single, Crossover, Triple Hop LSI:

$$\frac{\text{Involved (6 months)}}{\text{Uninvolved (6 months)}} \times 100$$

6-meter Timed Hop LSI:

$$\frac{\text{Involved (6 months)}}{\text{Uninvolved (6 months)}} \times 100$$

Quad Strength EPIC:

$$\frac{\text{Involved (6 months)}}{\text{Uninvolved (Initial Evaluation)}} \times 100$$

Single, Crossover, Triple Hop EPIC:

$$\frac{\text{Involved (6 months)}}{\text{Uninvolved (Impairment Resolution)}} \times 100$$

6-meter Timed Hop EPIC:

$$\frac{\text{Uninvolved (Impairment Resolution)}}{\text{Involved (6 months)}} \times 100$$

Figure 1: LSI vs EPIC Scales.[22]

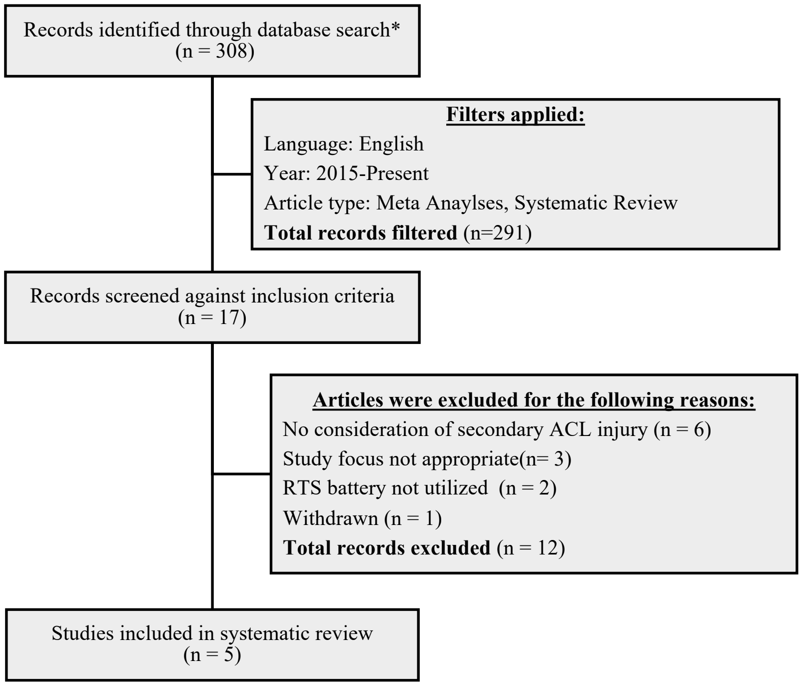


Figure 2: Study Selection
Search was conducted on December 1, 2020, in the PubMed Database, examining Titles and Abstracts for the following search terms: (Anterior Cruciate Ligament OR ACL) AND (Reconstruction) AND (return to sport OR RTS) AND (Assess* OR Tool* OR Test*) AND (injury OR reinjury).

Table 1: Summary of Search Methodologies

Review	Databases	**Search Dates:** Key Terms	Inclusion Criteria	Studies (Participants)
Barber-Westin & Noyes[27] 2020	- Cochrane Library - PubMed	**Inception- May 31, 2019:** Anterior cruciate ligament pediatrics, ACL return to sport, anterior cruciate ligament children, anterior cruciate ligament reconstruction children, anterior cruciate ligament reconstruction adolescent, ACL adolescent, ACL skeletally immature, ACL transphyseal	1) English 2) Primary transphyseal ACL reconstruction in patients <20 years old 3) Minimum mean follow-up of two years postoperatively 4) Report ACL graft reinjury rate 5) Report the percentage of patients that returned to sport postoperatively	**8** (1,239)
Losciale et al.[28] 2019	- CINAHL - Embase - Medline - ProQuest Dissertations and Theses Global - PubMed - SPORTDiscus	**Inception - March 2018:** Anterior cruciate ligament, surgery, surgical, repair, reconstructive, reconstruction, graft, autograft, return to sport, return to sports, return to play, return to competition, return to, return to duty, return to activity	1) English 2) Patients recovering from ACLR with any graft type (may have concomitant meniscus lesion and/or MCL lesion) 3) Study population age between 10 and 50 years 4) Use clearly defined objective criteria to make the RTS decision 5) Determine and report the number of patients who passed versus failed RTS criteria 6) Track patients for subsequent ACL injury following RTS	**4** (576)
Webster & Hewett[29] 2019	- CINAHL - Embase - Medline - PubMed - SPORTDiscus - 'Articles in press hand search from top sports medicine journals'	**Inception - May 7, 2018**: Anterior cruciate ligament reconstruction, ACL reconstruction, return to sport, return to sport criteria, return to play, return to play criteria, functional testing, return to athletic	1) English 2) Participants who had undergone ACL reconstruction (primary or revision) surgery 3) Utilized an RTS battery (no minimum number of tests required, however, multiple domains needed to be represented (strength, hop, function) 4) Reported the number of participants who passed the test battery or were cleared for RTS based on test battery results.	Qualitative Synthesis: **18** (2,000) Meta-Analysis: **16** (variable)
Ashigbi et al.[31] 2020	- Cochrane Library - Google Scholar - PubMed - Web of Knowledge - guidelines.gov - opengrey.eu - clinicaltrials.com - controlled-trials.com.	**Inception - March 2018**: Anterior cruciate ligament, re-rupture, recurrence, re-rupture, graft failure, re-injury, secondary, risk, discharge criteria, function, postural control, balance, hop, isokinetic, strength, isometric, limb symmetry index, jump, performance	1) English or German 2) Original prospective cohort research articles published before March 2018 3) Male and female adolescents and adults involved in sports, who suffered a primary unilateral ACL rupture, had subsequent reconstruction and rehabilitation.	**8** (6,140)
Losciale et al.[35] 2020	- CINAHL - ClinicalTrials.gov - Cochrane Library - Embase - Medline - PubMed - SPORTDiscus	**Inception - January 19, 2018**: ACLR, hop testing, return to sport, functional performance testing	1) English 2) Published in a peer-reviewed journal 3) Study population average age: 10-50 years 4) Patients attempting to RTS 5) Patients with any ACLR graft type (may have a concomitant meniscal lesion, chondral lesion, bone bruise, and/or MCL lesion less than grade 3 6) Reported data on hop test procedure description and objective performance data 7) Reported data on 1+ primary outcome variables. 8) Statistically measured association, correlation or effect size of hop testing results and 1+ primary outcome variables or performed between-group comparisons with hop test result as an independent variable	**21** (4,476)

Table 2: Characteristics of Included Studies

Review	Objective(s)	**RTS Tests Used** (Pass criteria if applicable)	Major Results
Barber-Westin & Noyes[27] 2020	Determine RTS rates; the effect of high-risk sport participation, sex, and graft type on ACL reinjury rates, and; whether objective test criteria before RTS correlate with lower reinjury rates.	- **Strength**: Isometric quadriceps (LSI≥85%) - **Hop**: Single, triple, (LSI≥90% for all) - **Functional**: "restoration of jump landing and pivoting mechanics," "according to an objective assessment of whether the rehabilitation goals have been met"	- 87% returned to sport; 80% high risk activity - 18% ACL re-injury (range: 3% to 34%); 10% graft failure; 10% contralateral ACL; 2% both. - 90% of graft failures and 80% of contralateral ACL failures occurred during high-risk sports - Males had higher rate of graft failure than females (13% and 8%, respectively; OR 1.64; p=0.01); No sex-based effect on contralateral ACL injury. - Hamstring autograft failure rate was higher than patellar tendon autograft failure rate (15% and 9%, respectively; OR 0.52; p=0.002).
Losciale et al.[28] 2019	Determine if criteria based RTS decisions correlated with lower risk of secondary ACL injury; report/classify RTS criteria; report passing cutoff scores; determine pass/fail incidence and reinjury rates; assess diagnostic accuracy of RTS tests	- **Strength**: Isometric quadriceps (LSI>90%), isokinetic HQ ratio (LSI>85% at 60º/s and 180 º/s, or LSI>90% at 60º/s) - **Hop**: Single, 6-m timed, triple, triple crossover (LSI>90% for all) - **Jump**: triple, vertical (LSI>90% for all) - **Functional**: OFSSR (complete) - **Agility**: T-Test (<11 seconds) - **Self-report**: KOS-ADL (>90%), GRS (>90%)	- 42.7% passed RTS criteria (95% CI: 18, 69%) -Passing RTS criteria lead to a nonsignificant: (1) decrease in secondary ACL injury (RD -3%; 95% CI: -16%, 10%; I^2=74%; p=0.610) (2) decrease in secondary graft injury (RD -7%; I^2=74%; p=.140) (3) increase in secondary contralateral ACL injury (RD 4%; I^2=28%; p=.160)
Webster & Hewett[29] 2019	Determine proportion of patients who passed RTS test batteries after ACLR; whether passing RTS batteries increased rates of RTS and; whether passing RTS test batteries reduced subsequent knee and ACL injury.	- **Strength**: Isometric HQ ratio (LSI≥85% or 90%; EPIC≥90%) - **Hop**: single, vertical, 6m-timed, triple, triple crossover, side, star excursion (LSI≥90%; EPIC≥90% for all) - **Jump**: Vertical, tuck, triple, counter movement, speedy, plyometric, DVJ, LESS, 5 jump test (LSI≥90% for all) - **Functional**: OFSSR, stability tests - **Agility:** T-Test (<11 seconds), quick feet test - **Self-report**: KOS-ADL, GRS, IKDC (≥90%), ACL-RSI	-23% of patients passed RTS test batteries -Passing RTS battery lead to greater RTS rates -Passing RTS battery did not reduce risk for risk for all subsequent ACL injuries (RR 0.28; 95% CI: 0.04, 0.94; p=0.09); Passing RTS battery decreased risk of graft rupture (RR 0.080, (95% CI: 0.27-2.3; p=0.07), but increased risk of subsequent contralateral ACL injury (RR 3.35; 95% CI: 1.52-7.37; p=0.003). -See Table 3 (Appendix) for additional results
Ashigbi et al.[31] 2020	Provide an overview of evidence based RTS assessments with an assessment of the risk for an ACL re-injury.	- **Strength**: Isometric quadriceps (LSI>90% at 60º knee flexion), isokinetic HQ ratio*[A] (LSI>90% at 60 º/s, 180º/s and 360º/s) - **Hop:** single*[B], 6-m timed, triple*[C], triple crossover*[D] (LSI>90% for all) - **Jump**: triple (LSI≥90%) **- Functional**: OFSSR*[F] (complete), DVJ 3D-motion analysis and postural stability (Table 4) **- Agility**: T-Test*[E] (<11 seconds) **- Clinical**: PTS (OsiRix: PTS > 12º), dynamic assessment with CompuKT at 20º knee flexion **- Self-report:** IKDC, TSK-11(≥17 or ≥19), GRS (>90%), KOOS-QoL (<44), KOS-ADL (>90%), Marx Activity Rating Scale (≤15)	-Secondary ACL injury rate: range 1.5% to 37.5% - EPIC <90% (strength, hop tests) is predictive of secondary ACL injuries (sensitivity: 0.818; 95% CI: 0.523, 0.949) -PTS was significantly higher in patients who experienced secondary ACL injury (9.9 - 11º) than no secondary ACL injury (8.5 – 9º; p=0.001) -PTS ≥ 12º was associated with increased risk of ACL rupture (RR 2.54; 95% CI 1.6, 4.0; p<0.0001) The risk of graft rupture was increased when: (1) TSK-11≥19 (RR 13.0; 95% CI: 2.1, 81.0; p=0.03) (2) Isokinetic HQ ratio (60°/s) is decreased (HR 10.6 per 10% difference, 95% CI: 10.2, 11; p=0.005). (3) 1+ discharge criteria*[A-F] was not achieved before RTS (HR 4.1, 95% CI: 1.9, 9.2; p≤0.001) -3D analysis combining 4 variables predicted secondary ACL injury; hip rotation moment independently predicted ACL injury (Table 4)
Losciale et al.[35] 2020	Determine the strength of association between hop testing and RTS, knee reinjury, self-report of knee function, and PTOA after primary ACLR; determine if hop testing can predict the same outcome variables.	-**Hop Tests**: Single, triple, crossover, 6m-timed, 12m-timed, vertical, side (LSI>90% for all) -**Self-Report**: KOOS, Noyes, IKDC, Tegner, Marx Activity Scale	-6m-timed hop LSI>90% correlated with reduced secondary ACL injury (HR 0.97; 95% CI: 0.93, 1.02; p=.20); All other hop tests had no significant predictive capability of secondary ACL injury -IKDC & hop test (r = 0.20 to 0.60) -KOOS & hop test (r = -0.10 to 0.62) -Preoperative hop LSI≤ 75% associated with 2.9x greater risk for PTOA development within 10 years post-ACLR (95% CI: 1.2, 7.1; p=0.02) -No statical difference in 23 years post-ACLR hop LSI scores (single hop, vertical jump, side hop) in patients with and without knee PTOA.

Note: Time since ACLR was not included in this table.

Table 3: Findings from Webster & Hewett[29]

Passing RTS Battery Rates and Correlation with Outcome Variables	Studies (Patients)
23% of patients passed RTS battery <u>before</u> RTS (95% CI: 8, 43%; I^2=97.5%) - Pass rates ranged from 0-79% across the studies. - Patients were tested between 5- and 10-months post-ALCR	**8** (876)
23% of patients passed RTS batteries <u>after</u> returning to strenuous sports (95% CI: 18, 29%; I^2=0%)	**3** (234)
Passing an RTS battery 6 months post ACLR lead to higher RTS rates and 12 and 24 months post-ACLR - Passing RTS battery at 6 months post ACLR led to RTS rates of 80% and 84% (12- and 24-months post ACLR, respectively) - Failing RTS battery at 6 months post ACLR led to RTS rates of 44% and 46% (12- and 24-months post ACLR, respectively)	**1** (95)
Passing an RTS battery did not predict whether pre-injury Tegner score would be achieved at a minimum 2-year follow-up - 51% of patients who passed RTS criteria achieved their pre-Injury Tegner score - 52% of patients who failed RTS criteria achieved their pre-Injury Tegner score.	**1** (223)
Passing an RTS battery did not result in a significant reduction in knee injury (RR 0.28; 95% CI: 0.04, 0.94; p=0.09; I^2=13%) - 10.9% of patients who passed RTS criteria experienced a subsequent knee injury - 37.3% of patients who failed RTS criteria experienced a subsequent knee injury	**2** (114)
Passing an RTS battery had minimal effect on RR of all ACL injuries (RR 0.80; 95% CI:0.27, 2.3; p=0.7; I^2=79%) - 13.7% of patients who passed RTS battery experienced a subsequent ACL injury - 14.2% of patients who failed RTS battery experienced a subsequent ACL injury	**5** (565)
Passing RTS battery significantly decreased risk of graft rupture (RR 0.40; 95% CI: 0.23, 0.69; p < 0.00; I^2=0%) - 7.6% of patients who passed RTS battery experienced a subsequent graft rupture - 11.3% of patients who failed RTS battery experienced a subsequent graft rupture	**5** (565)
Passing RTS battery significantly increased risk of contralateral ACL injury (RR 3.35; 95% CI:1.52, 7.37, p=0.003; I^2=0%) - 10.9% of patients who passed RTS battery experienced a subsequent contralateral ACL injury - 3.5% of patients who failed RTS battery experienced a subsequent contralateral ACL injury	**4** (407)

Table 4: Findings from Paterno et al.[34]

3D Motion Analysis of DVJ and Postural Stability Assessment	Patients
1) Decreased hip external rotator moment during early landing was associated with secondary ACL injury OR = 8.4; 95% CI: 2.1, 33.3; p < .001); - **Injury group**: Net hip internal rotator moment (−2.4 × 10^{-3} Nm/kg) - **Injury free group**: Net hip external rotator moment (1.1 × 10^{-3} Nm/kg).	Total (n = 56) Secondary injury within 24 months post-ACLR (n = 13) Injury free after 24 months post-ACLR (n = 43)
2) Increased frontal plane knee joint motion during landing was associated with secondary ACL injury (OR = 3.5; 95% CI: 1.3, 9.9; p=0.03) - **Injury group**: Mean total frontal plane (valgus) movement: 16.2µ - **Injury free group**: Mean total frontal plane (valgus) movement: 12.1µ	
3) Asymmetries in sagittal plane knee moments at landing was associated secondary ACL injury (OR = 3.3; 95% CI: 1.2, 8.8; p=0.03) - **Injury group**: uninvolved limb −2.8 × 10^{-2} Nm/kg; involved limb: 9.5 × 10^{-2} Nm/kg; Difference: 12.3 × 10^{-2} Nm/kg - **Injury free group**: uninvolved limb 8.4 × 10^{-2} Nm/kg; involved limb 11.4 × 10^{-2} Nm/k; Difference: 3.0 × 10^{-2} Nm/kg	
4) Deficits in single leg postural stability of involved limb were associated with secondary ACL injury (OR = 2.3; 95% CI: 1.1, 4.7) - **Injury group**: Mean degree of deflection (involved limb): 4.07° ± 2.06° - **Injury free group**: Mean degree of deflection (involved limb): 3.63° ± 1.58°	
* Combining variables 1-4 predicted secondary ACL injury (C-statistic = 0.94; sensitivity = 0.92; specificity = 0.88) ** Variable 1 independently predicted secondary ACL injury (C-statistic = 0.81l; sensitivity = 0.77; specificity = 0.81)	

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Acknowledgements

I would first like to thank my mentor, Dr. Dan Ogborn for sharing his expertise and guidance throughout this Capstone project. I would also like to thank the MPAS program faculty, staff, and my classmates for their continued support over the past two years. Finally, I would like to thank my parents, Craig and Barbara Sheard, for their lifelong love and encouragement.