Comparison of anterior cruciate ligament loading during two functional tasks in rehabilitated athletes

An evaluation of the ACL load using musculoskeletal modeling

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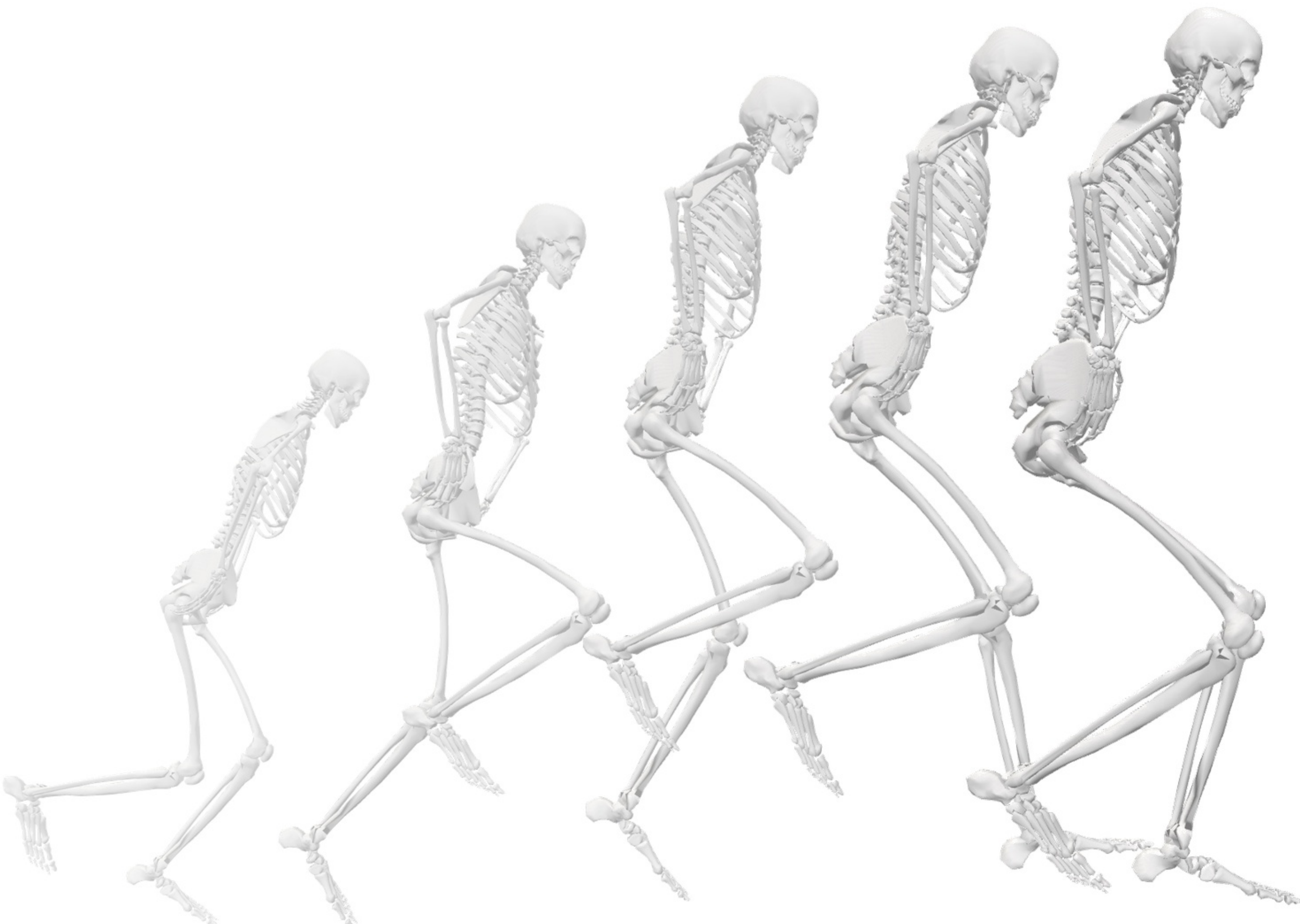

TU Delft

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by

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Abstract

The anterior cruciate ligament (ACL) is a critical stabilizer of the knee joint, and ACL injuries are common in pivoting sports such as soccer, basketball, and handball. Following ACL reconstruction (ACLR), determining when an athlete can safely return to sport (RTS) remains a clinical challenge, with reinjury rates reported as high as 20% or more. Current RTS assessment tools, such as the single leg hop for distance (SLH) and unilateral countermovement jump (uCMJ), primarily quantify whole-limb performance symmetry between limbs rather than directly capturing the mechanical load on the reconstructed ligament.

This study aimed to quantify and compare ACL loading during the SLH and uCMJ in 19 ACLR-rehabilitated athletes using musculoskeletal modeling and a vector-projection ACL force estimation approach in OpenSim. Two comparisons were made: impaired versus unimpaired limb, and athletes who had versus had not regained their pre-injury sport activity level, and to the healthy controls. A lower-limb musculoskeletal model was scaled to each participant, followed by inverse kinematics, inverse dynamics, and static optimization to estimate muscle forces and knee joint reaction forces (JRFs). ACL load was estimated by projecting the anterior-posterior and medial-lateral JRF components onto the instantaneous ACL orientation vector, with an additional indirect contribution from tibial slope accounted for.

No significant differences in ACL peak load, JRFs, or knee kinematics were found between the impaired and unimpaired limbs, or between the ACLR group and healthy controls. Peak ACL loads were approximately $3.2bw$ during the SLH and $2.8bw$ during the uCMJ across all three groups. This absence of asymmetry is likely attributable to the long average follow-up period of approximately 3.8 years post-injury, which exceeds the typical RTS clearance timeframe, suggesting that compensatory movement strategies had largely resolved by the time of testing.

When comparing athletes who had and had not regained their pre-injury activity level, the not regained group showed significantly lower peak ACL loads during the SLH ($2.6bw$) compared to the control group ($3.2bw$) and the regained group ($3.5bw$), as confirmed by post-hoc analysis. A similar pattern was observed during the uCMJ, where the not regained group again showed the lowest peak load ($2.3bw$), compared to $2.8bw$ in controls and $3.1bw$ in the regained group, though this difference did not reach statistical significance in post-hoc analysis. This reduced loading may reflect a deliberate unloading strategy, a more cautious rate of loading, and the biomechanical effect of a more extended knee posture, which reduces both quadriceps demand and the scalar projection of joint forces onto the ACL vector.

Across both tasks, the SLH produced higher peak ACL loads than the uCMJ and demonstrated greater sensitivity in detecting between-group differences, supporting its value as a clinically relevant assessment tool even when performed under submaximal conditions. Key limitations include the small and imbalanced sample in the not regained group, the use of a 1 degree of freedom (DoF) knee model, the absence of EMG data, and the use of generic rather than subject-specific ACL attachment coordinates. Future work should incorporate a higher DoF knee model, EMG-informed optimization, and testing of athletes at earlier rehabilitation stages to better capture ACL loading deficits near the time of RTS clearance.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
ACL	Anterior cruciate ligament
ACLR	Anterior cruciate ligament reconstruction
ANOVA	Analysis of variance
AP	Anterior-posterior
CMC	computed muscle control
DoF	Degrees of freedom
EMG	Electromyography
GRF	Ground reaction force
IGC	Initial ground contact
JRF	Joint reaction force
LCL	Lateral collateral ligament
LSI	Limb symmetry index
MCL	Medial collateral ligament
ML	Medial-lateral
RMR	rapid muscle redundancy
RTS	Return to sport
SLH	Single leg hop for distance
SO	Static optimization
SPM	Statistical parametric mapping
uCMJ	Unilateral countermovement

1 Introduction

1.1. Background

The anterior cruciate ligament (ACL) is a critical structure in the knee joint and plays an essential role in maintaining joint stability during dynamic movements by preventing excessive anterior tibial translation and controlling rotational stability of the tibia relative to the femur. Anatomically, the ACL primarily resists anterior tibial translation relative to the femur and contributes to controlling rotational stability of the knee [1–3]. These stabilizing functions are particularly important during pivoting sports that involve rapid deceleration, cutting, and changes of direction.

ACL injuries are therefore common in sports that require such dynamic maneuvers, often referred to as level I sports, including soccer, basketball, and handball. It has been reported that 1 in 29 female athletes and 1 in 50 male athletes experience an ACL rupture over a time frame between one season to 25 years [4]. Considering this, along with the fact that rehabilitation typically requires around 222 days [5], underscores the detrimental of this injury.

The primary goal of ACL reconstruction (ACLR) and rehabilitation is to restore knee stability and function, enabling individuals to safely return to their previous level of sport participation. However, despite the research progress in rehabilitation practice, studies have reported that the risk of experiencing an ipsilateral ACL reinjury may reach 20% or higher after return to sport [6, 7].

Determining when an athlete can safely return to sport is therefore a key component of post-ACLR management. The return to sport (RTS) decision-making process aims to balance a timely return to athletic participation with the need to minimize the risk of reinjury [8].

1.2. RTS assessment and decision-making

RTS assessment after ACL reconstruction integrates a range of criteria, both objective and subjective. Despite the wide range of these criteria, no consensus exists on which combination of factors best determines readiness to RTS, resulting in largely non-standardized assessment batteries across studies [8]. Each rehabilitation process consists of several different test (test batteries) used to evaluate if an athlete can safely RTS. Commonly RTS evaluation includes functional performance tests (e.g., hop, jump, strength, and balance tests), psychological readiness measures, and time since surgery. The primary goal of these criteria is to reduce the risk of reinjury while allowing athletes to safely resume sport participation [8]. Although RTS test batteries are widely implemented, the evidence supporting their effectiveness remains limited and heterogeneous [9–11].

Among the functional performance tests that have been researched, the single leg hop for distance (SLH) and unilateral countermovement jump (uCMJ) have shown promise in identifying athletes at lower risk of reinjury, as better performance outcomes on these tests have been associated with reduced reinjury rates [12, 13]. Consequently, these tests are frequently included in RTS assessment batteries [Appendix A]. Performance outcomes such as hop distance and jump height are typically used to determine limb symmetry through the limb symmetry index (LSI), which is calculated as the ratio of the impaired to the unimpaired limb expressed as a percentage, with a threshold of 90% or higher commonly used for RTS clearance. However, studies have shown that even when this criterion is met, underlying deficits may still be present [14, 15].

Despite their widespread use, these functional tests primarily assess global lower-limb performance rather than knee-specific function [Appendix A]. Movements such as hopping and jumping rely on the coordinated contributions of the hip, knee, and ankle joints. As a result, athletes may compensate for deficits at the knee by altering movement strategies at other joints, potentially masking underlying impairments in knee stability or ligament loading [15].

Although multi-test batteries appear to be more effective than isolated criteria [12, 16], the biomechanical mechanisms underlying their predictive value remain poorly understood. In particular, it remains unclear how performance-based outcomes from functional tests relate to the mechanical demands placed on the reconstructed ACL during dynamic sport-related movements [14, 15].

1.3. Anatomy of knee

The knee joint is the largest and one of the most complex joints of the human body. Unlike the hip joint, which derives much of its stability from the deep bony socket of the acetabulum, the knee joint is less congruent, meaning that movement constraints are provided more by soft tissues and ligaments than by bone geometry, see Figure 1.1 [1, 2].

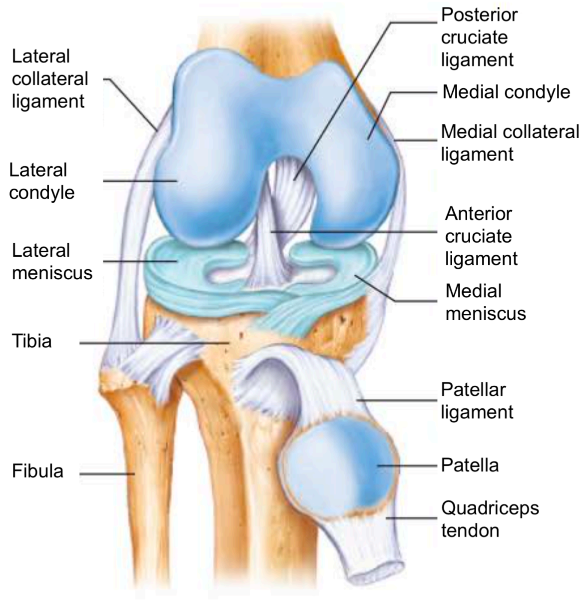


Figure 1.1: Anterior view of the tibiofemoral joint [1].

The skeletal bones of the knee consist of the femur, tibia, and patella, which together form the tibiofemoral and patellofemoral joints. The working mechanism can be best described as a joint where flexion and extension is the primary motion [1–3]. It also permits limited rotation as the external condyle moves from anterior to posterior [2]. Because bony congruency offers limited inherent stability, the passive stabilizing role of the ligaments is of particular importance.

The primary ligaments of the knee are the ACL, posterior cruciate ligament (PCL), medial collateral ligament (MCL), and lateral collateral ligament (LCL). These structures primarily prevent excessive translation and rotation of the tibia relative to the femur, thereby maintaining joint integrity [1–3].

The ACL is the primary restraint against anterior tibial translation, preventing the tibia from sliding forward relative to the femur. While being able to prevent $62–87\%$ of all the anterior shear force, it also contributes to rotational knee stability during dynamic movements [1–3]. Given that many sport related activities such as deceleration, cutting, and landing generate high anterior shear forces, the ACL is particularly vulnerable to injury under these loading conditions [3].

The PCL, by contrast, primarily restrains posterior tibial translation, preventing the tibia from sliding backward relative to the femur [1, 2]. The MCL and LCL, in turn, are important for medial and lateral stability, respectively, by resisting valgus and varus stress [1, 2].

1.4. Knee model

Recent advances in musculoskeletal modeling have led to the development of knee joint models with multiple degrees of freedom (DoF). Standard lower-limb models, such as those commonly used for gait analysis, typically represent the tibiofemoral joint as a 1DoF joint, where the other (secondary) kinematics are prescribed as functions of knee flexion angle based on cadaveric walking data [17]. This approach is computationally efficient, however its biggest downfall is that the flexion-extension is the sole independent coordinate. Meaning that tibial translation or rotation (such as the anterior tibial translation that loads the ACL) cannot be independently captured but is instead prescribed as a fixed function of knee flexion angle, regardless of the actual loading conditions.

More advanced tibiofemoral models such as the 6DoF, in which ligaments and articular contact surfaces govern secondary knee kinematics, offer the ability to more directly simulate ACL strain and force during dynamic tasks [18, 19]. However, these models are computationally more demanding and are mostly subject-specific, which is not always available in large cohort studies [20].

1.5. Gap and aim

A key limitation of current RTS assessments is that most tests provide indirect measures of knee function. Functional tests such as hop and jump assessments quantify performance outcomes, but they do not directly capture the mechanical behavior of the ACL during dynamic tasks. As a result, it remains unclear how the performance metrics (such as hop distance and jump height) used in RTS testing relate to the actual loading conditions experienced by the reconstructed ligament.

Recent advances in biomechanical modeling and musculoskeletal simulation offer the potential to estimate ligament loading during movement tasks. Kotsifaki et al. were among the first to show that biomechanical analysis of the SLH can reveal asymmetries in knee loading that are not captured by standard performance metrics such as the LSI [14]. Such approaches could provide more direct insight into ACL loading patterns and help bridge the gap between functional performance tests and underlying knee biomechanics.

A limited number of studies have estimated ACL loading during sport-related tasks using musculoskeletal modeling and simulation, with approaches ranging from using joint moments to muscle excitations combined with the Hill muscle model, and these studies have focused on specific movements such as side steps, drop jumps or sudden stops [21–25]. However, no study has systematically compared ACL loading patterns across commonly used functional RTS tasks in a larger cohort of rehabilitated athletes.

Therefore, the purpose of this study is twofold: (1) to develop and test a novel method that estimates ACL load directly from the joint reaction force, and (2) to quantify and compare ACL loading patterns during the SLH and uCMJ in ACLR-rehabilitated athletes. The analysis mainly focuses on peak ACL loads, as this represents the highest mechanical demand placed on the reconstructed ligament during the landing phase. Additionally the knee joint reaction force components and knee joint kinematics, to identify potential compensatory movement strategies, will also be looked at. Comparisons will be made between impaired and unimpaired limbs, as well as between impaired leg of the returned-to-sport athletes, non-returned athletes, and healthy controls.

2 Methodology

2.1. Dataset

For this research an open access dataset has been used [26]. The dataset consists of marker and ground reaction force (GRF) data of 44 participants undergoing a jump protocol consisting of six different jumps. Four unilateral jumps (SLH, uCMJ, unilateral crossover hop and, unilateral medial-rotation hop) and two bilateral jumps (CMJ and drop jump). For the purpose of this research only the SLH and uCMJ are evaluated, since they are unilateral, and widely used in RTS assessment. The dataset also included jumps where the participant was fatigued, as this was not the focus of this research, these were not included.

2.1.1. Participation

From the dataset 19 participants were found eligible to be used in this research. These participants were included if: (1) they had an ACL injury and (2) underwent an ACLR. Table 2.1 summarizes the demographic data of the participants.

Two comparisons were performed in this study: (1) a within-participant comparison between the impaired and unimpaired limb, and (2) a between-group comparison based on return to pre-injury sport activity level. For the limb-level comparison, all 19 participants were included, and outcomes of the impaired limb were compared to those of the contralateral unimpaired limb within the same individual. For the between-group comparison, participants were categorized based on if they had returned to their previous level of sport activity (not regained: n = 3 and regained: n = 16). In this comparison, only data from the impaired limb were included to evaluate differences associated with recovery status.

Table 2.1: Demographic information of the different groups made for the comparison (ACL group, control, not regained, and regained).

Demographic Info	ACL Group	Control	Not regained	Regained
Gender (m; f)	10; 9	8; 12	1; 2	8; 8
Age (y)	24.4 $\pm$ 3.6	26.3 $\pm$ 3.2	26.3 $\pm$ 8.4	24.0 $\pm$ 2.4
Height (m)	1.75 $\pm$ 0.1	1.72 $\pm$ 0.1	1.77 $\pm$ 0.1	1.74 $\pm$ 0.09
Weight (kg)	69.3 $\pm$ 11.0	67.0 $\pm$ 14.1	76.7 $\pm$ 14.4	68.0 $\pm$ 10.2
BMI (kg/m^2)	22.6 $\pm$ 1.7	22.4 $\pm$ 2.3	24.2 $\pm$ 1.9	22.3 $\pm$ 1.5
Leg dominance (l; r)	2; 17	2; 18	1; 2	8; 8
Injury side (l; r)	9; 10	–	1; 2	8; 8
Time since injury (y)	3.8 $\pm$ 2.6	–	2.3 $\pm$ 1.2	4.1 $\pm$ 2.7
Duration of rehab* (m)	8.0 $\pm$ 4.0	–	7.0 $\pm$ 4.4	8.19 $\pm$ 4.1
Reinjury	0	–	0	0

* from surgery till the end of the physiotherapy sessions.

2.1.2. Jump protocol

For the SLH, participants started at a standardized distance of 100% of their leg length away from the force plate. Leg length was defined as the distance from the anterior superior iliac spine to the lateral malleolus of the dominant leg. Participants were instructed to stand on the leg to be tested and their hands on their hips, hop forward, and land on the same leg in the middle of the force plate.

For the uCMJ, participants stood with the leg to be tested positioned in the middle of the force plate, and with their hands on their hips. The jump started with a single leg squat to a self-selected depth, followed by a maximal vertical acceleration. Participants were instructed to jump as fast and as high as possible. The swing leg was kept at approximately $90°$ knee flexion and was not allowed to contribute to propulsion.

2.1.3. Data processing

Marker trajectories and GRFs were low-pass filtered using a zero-lag, 4th-order Butterworth filter with a cutoff frequency of $20Hz$. Although $15Hz$ is more commonly reported in similar studies [14], a cutoff of $20Hz$ was selected to better preserve peak GRF magnitudes, which would otherwise be attenuated at lower cutoff frequencies [21, 27]. This was considered important given that peak ACL loading is hypothesized to occur immediately after landing. A higher cutoff frequency is preferable as long as it does not affect the convergence of the to perform analyses. No convergence issues were observed at this cutoff frequency in the present study, making $20Hz$ a suitable choice.

As recommended, the marker trajectories and GRFs were transformed to align with OpenSim's coordinate system by swapping the y and z axes and negating the y axis, which effectively applies a 90 degree rotation about the x axis. Furthermore, the torque components of the GRF have been transformed from mm to m, to make it suitable for the analysis in OpenSim's. The landing phase was defined as the interval from initial ground contact (IGC) to a time point equal to three times the duration between IGC and peak ACL loading. IGC was identified as the first time point where the vertical GRF component exceeded a threshold of $30N$.

Statistical analysis was performed using statistical parametric mapping (SPM), a method designed for the analysis of time-series data. Unlike traditional scalar statistics, SPM evaluates the entire time series rather than discrete time points, making it particularly suitable for biomechanical waveform data, where differences between groups may occur over a continuous interval rather than at a single instant [28]. An one-way ANOVA was conducted to assess between-group differences at each time point across the landing phase. The resulting SPM{F} statistic was compared with a critical threshold, determined at a significance level of $\alpha = 0.05$. Where statistical significance was reached, a post-hoc analysis was performed to identify which groups differed. The same significance level was used as for the one-way ANOVA.

Following data processing, several trials were excluded from further analysis. Trial s23_CMJ_r_t1 was removed due to a labelling error, and s39_CMJ_r_t1 was excluded due to a corrupted marker file resulting in high right heel marker error. The trial s10_CMJ_l_t2 was also removed because static optimization reached saturation, resulting in a large ankle reserve actuator. Across all retained trials, marker tracking quality was within acceptable limits (see Appendix B).

2.2. Neuromusculoskeletal modeling

The generic lower-limb model developed by Catelli et al., which is based on the Rajagopal model, was used to perform musculoskeletal simulations in OpenSim [29]. This model is suitable for tasks involving high hip and knee flexion. It contains 80 muscles and 39 coordinates. A total of eight coordinates were locked, including wrist flexion and deviation in both arms, as well as the subtalar and metatarsophalangeal joints of both feet. The remaining 31 coordinates included 10 upper body coordinates, which were actuated by coordinates actuators only, as not muscles were modeled. Of the 21 lower body coordinates, 15 were present in the leg. Since these coordinates were actuated by muscles, coordinate actuators were added as reserve actuators to account for residual moments. The knee flexion beta coordinates at both legs, however, had no actuators modeled as their motion is fully driven by the knee angle coordinates due to constraints. Additionally, three translational (force) and three rotational (moment) residual actuators were applied to the pelvis to account for unmodeled dynamics, modeling inconsistencies and ensuring dynamic consistency.

The hip was modeled as a 3DoF ball-and-socket joint, the knee as a 1DoF joint based on the Walker knee model with flexion–extension as the independent coordinate [17], and the ankle as a 1DoF pin joint

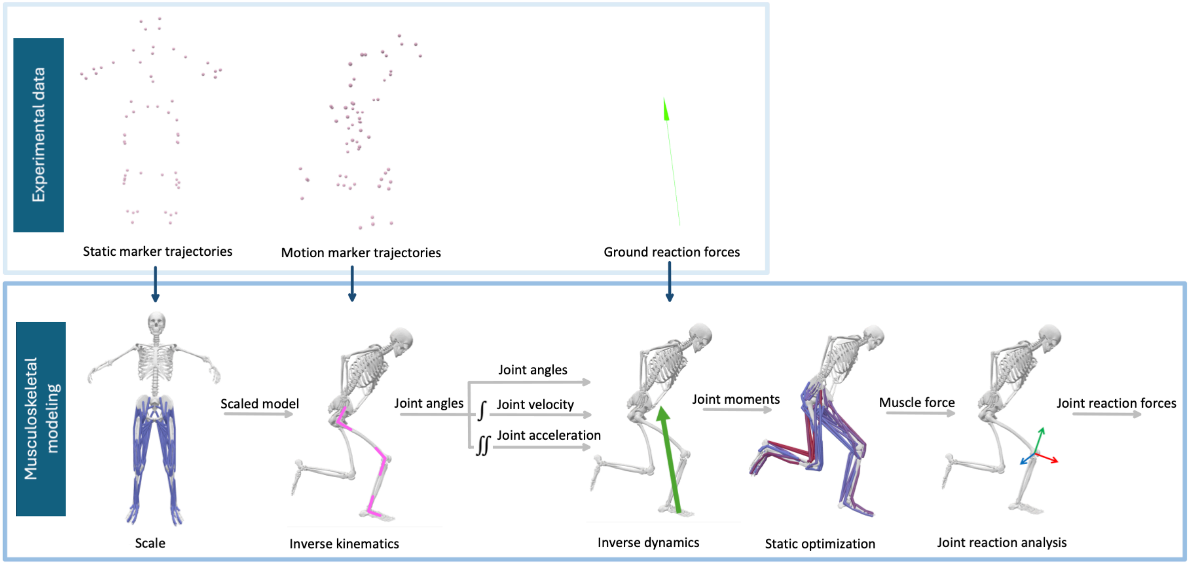


Figure 2.1: OpenSim pipeline utilized in the presented study.

To compensate for underestimation of muscle strength in models during dynamic jump-landing tasks, the isometric forces were multiplied by three, following the approach used in a previous study [15]. Musculoskeletal models are generally developed for gait or running tasks, and their muscle parameters are not optimized for the high joint moments that occur during dynamic landing tasks such as the SLH and uCMJ. Without muscle parameter scaling, static optimization (SO) reaches muscle activation saturation, meaning that the optimizer cannot find a feasible solution that satisfies the joint moment requirements within the physiological activation bounds. By increasing the isometric forces, the maximum available muscle force is increased, allowing the model to meet the required joint moments, while keeping the redundancy problem intact. Since SO minimizes the sum of squared muscle activations, scaling all isometric forces by a constant factor does not change the relative distribution of muscles forces. The optimization problem scales proportionally, meaning that the muscle force sharing pattern remains the same, while only the absolute force magnitudes are affected.

Linear scaling was performed for each participant by minimizing the error between model and experimentally measured marker positions using a nonlinear least-squares algorithm. The resulting scaling factors were then used to linearly scale segment dimensions and to adjust segment mass and inertia properties accordingly. Subsequently, inverse kinematics was performed to calculate joint angles by solving a weighted least-squares problem that minimizes the difference between experimentally recorded and model marker positions. Finally, inverse dynamics analysis was then performed to compute the net joint moments acting about each modeled DoF.

The calculated joint moments were subsequently resolved into individual muscle forces using a SO approach. This method, as described by Millard et al. [30], estimates muscle forces by minimizing the sum of squared muscle activations, following the optimization criterion proposed by Crownshield and Brand [31].

With the muscle force obtained from SO and the experimental GRF the knee joint reaction forces (JRFs) were obtained using the JointReaction analysis in OpenSim. Figure 2.1 summarizes the pipeline used in OpenSim.

2.3. ACL load estimation

To estimate the load acting on the ACL, a vector-based analysis was performed. The approach consisted of determining the orientation of the ACL during the landing phase and isolating the portion of the JRF that can be attributed to ACL loading.

2.3.1. Tracking ACL orientation

To determine the orientation of the ACL, the position and orientation of the femur and tibia were obtained from the OpenSim model by extracting the body transformations with respect to the ground reference frame. At each time step, the model state was updated with the joint coordinates and realized to the position stage, after which the transformation matrices of the femur and tibia were retrieved. These rotation and translation matrices were then used to express the anatomical origin and insertion points of the ACL in the local coordinate systems of the femur and tibia. The coordinates of the ACL origin and insertion are presented in Table 2.2. The ACL attachment coordinates of a healthy native ACL were used, as reported by Stanev et al. [32]. Subject-specific graft geometry was not available in this dataset.

For the purpose of this analysis, the ACL was modeled as a single bundle with a straight-line path between its origin and insertion, as was done by other peers as well [23, 25, 33]. This representation was then used in a vector projection to estimate ACL load throughout the landing phase.

Table 2.2: ACL attachment coordinates in child body frame [32].

Structure	Femur (origin)	Tibia (insertion)
ACL (right)	-0.01107, -0.40509, 0.00703	0.00954, -0.03130, -0.00037
ACL (left)	-0.01107, -0.40509, -0.00703	0.00954, -0.03130, 0.00037

(a) (b)

Figure 2.2: The ACL insertion (a) and origin (b) points of the left knee and their corresponding coordinates in child body frame (tibia and femur respectively) presented in the model.

2.3.2. Vector projection

The JRFs obtained from the JointReaction analysis represent the net force in the tibia coordinate system required to maintain joint stability, including contributions from structures that are not explicitly modeled, such as ligaments and bone-to-bone contact forces. The JRF can be decomposed into three components: compressive, medial-lateral (ML), and anterior–posterior (AP).

Of these, the ML and AP components represent shear forces that induce tibial translation, and therefore are the relevant drivers of ligament tension, including the ACL. The compressive force, however, could not be treated in the same way, as it primarily reflects bone-to-bone contact forces and its magnitude is considerably larger than the AP force. Including it directly in the projection would dominate the ACL load estimate and result in a non-physiological overestimation of ACL load. As the ACL does not resist compression, the compressive component was therefore excluded from the direct projection.

However, the compressive force does contribute to the ACL tension indirectly, through the geometry of the tibial plateau. The tibial plateau is posteriorly inclined, and when the femur is pushed on the tibia by the compressive force, a shear component is produced that translates the tibia anteriorly with respect to the femur. Thereby increasing tension to the ACL [3].

This indirect AP force contribution was estimated using a free body diagram of the tibial plateau, as illustrated in Figure 2.3. Next to the shear force parallel to the tibial plateau ($F_{shear,tibia}$), the compressive force induces a normal force perpendicular to the tibial slope ($F_{norm,tibia}$) as well. The formula for the shear force were found to be:

$$F_{\text{shear,tibia}} = \sin(\theta) \cdot F_{\text{comp}} \tag{2.1}$$

where the θ is the tibial slope angle. The corresponding indirect AP force ($F_{\text{AP,ind}}$) was obtained by resolving this shear component into the AP axis of the tibia reference frame, consistent with the coordinate system used for the JRF in OpenSim:

$$F_{\text{AP,ind}} = \frac{F_{\text{shear,tibia}}}{\cos(\theta)} \tag{2.2}$$

Substituting Equation 2.1 into Equation 2.2 results in the final equation:

$$F_{\text{AP,ind}} = \frac{\sin(\theta) \cdot F_{\text{comp}}}{\cos(\theta)} = \tan(\theta) \cdot F_{\text{comp}} \tag{2.3}$$

A population mean slope angle (θ) of $7.3°$ was used, based on the mean value reported in a study investigating 45 knees using MRI [34]. This corresponds to an increase of approximately 12.8% of the compressive force added to the AP component.

The total AP force was the defined as the sum of the AP component of the JRF obtained from OpenSim and the calculated indirect contribution, both represented in the tibia coordinate system defined by OpenSim. The ACL load was estimated by projecting this total AP force and the ML component onto the ACL orientation vector. Only the anterior component of the AP force was included, as the ACL does not resist any posterior shear force. This approach assumes that the ACL takes all the tensile force that can be projected onto the ACL vector direction. Since the compressive component itself was excluded from the projection, the problem is effectively reduced to two dimensions.

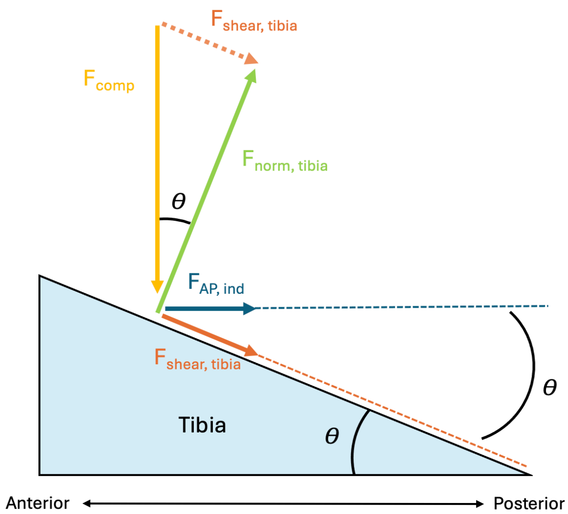


Figure 2.3: Free body diagram of the tibial plateau illustrating the decomposition of the compressive force (F_{comp}) into a shear component ($F_{shear,tibia}$) and a normal component ($F_{norm,tibia}$) along the tibial slope angle θ, and the resulting indirect anterior-posterior force contribution ($F_{AP,ind}$.

3

Results

3.1. General

This chapter presents the results of the two comparisons made in this study: the impaired versus unimpaired limb comparison, and the not regained versus regained comparison. Each comparison was compared to the control group as well. For each comparison, the ACL peak timing, ACL peak load, JRFs, joint angles, and GRFs are reported across the landing phase. All group means and standard deviations are summarized in Table 3.1 and Table 3.2.

3.2. Muscle force and reserve actuators

The quadriceps generated the largest muscular force contribution to the knee joint, followed by the soleus and the gluteus maximus, for both functional tasks. The gastrocnemius and gluteus minimus produced the smallest contributions. Detailed muscle force profiles for all conditions and tasks are provided in Appendix C (Figure C.1). Reserve actuator contributions were small (0.00061–$0.74bw$), indicating that the model scaling was appropriate (Figure C.2).

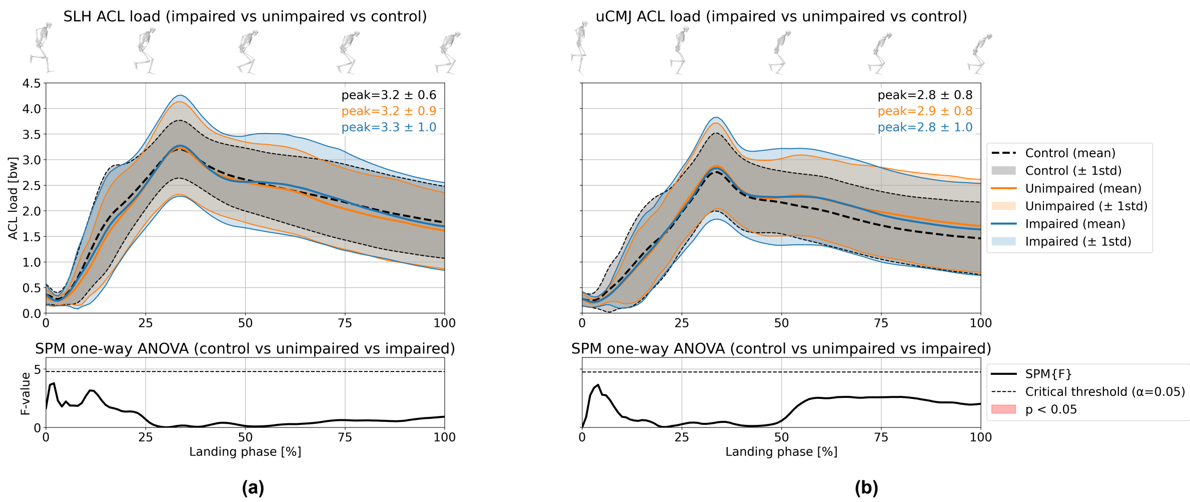


Figure 3.1: The ACL load (top) during the landing phase for the SLH (a) and uCMJ (b) of the impaired (blue), unimpaired (orange), and control (black) groups. The bottom figure shows the result of the one-way ANOVA.

3.3. Impaired vs unimpaired

3.3.1. Timing of ACL peak

The absolute timing of the ACL peak load for the SLH was around $0.13s$, and no clear difference between the groups were observed. This was earlier ($0.03 - 0.07s$) than those of the uCMJ.

3.3.2. ACL peak load

The graph of the ACL load had a sharp increase right after IC till the peak, after it gradually reduces, remaining above $1.5bw$ throughout the landing phase. This pattern was consistent for both tasks (Figure 3.1). During the SLH, all three groups reached a peak of approximately $3.2bw$, while during the uCMJ this was lower $2.8bw$. The one-way ANOVA revealed that the groups showed no significant differences for both the SLH and uCMJ.

3.3.3. Joint reaction forces

All three conditions showed a similar pattern relative to each other (Figure 3.2). The compressive forces were the largest, exceeding $10bw$. The impaired leg produced lower values compared to the other two conditions (SLH: $0.3bw$, uCMJ: $0.4bw$). The AP forces were the second largest, peaking at $2.4bw$ and $2.2bw$ for the SLH and uCMJ, respectively. The ML force were the smallest, and remained relatively small in comparison. Overall, the SLH accounted for higher JRFs than the uCMJ.

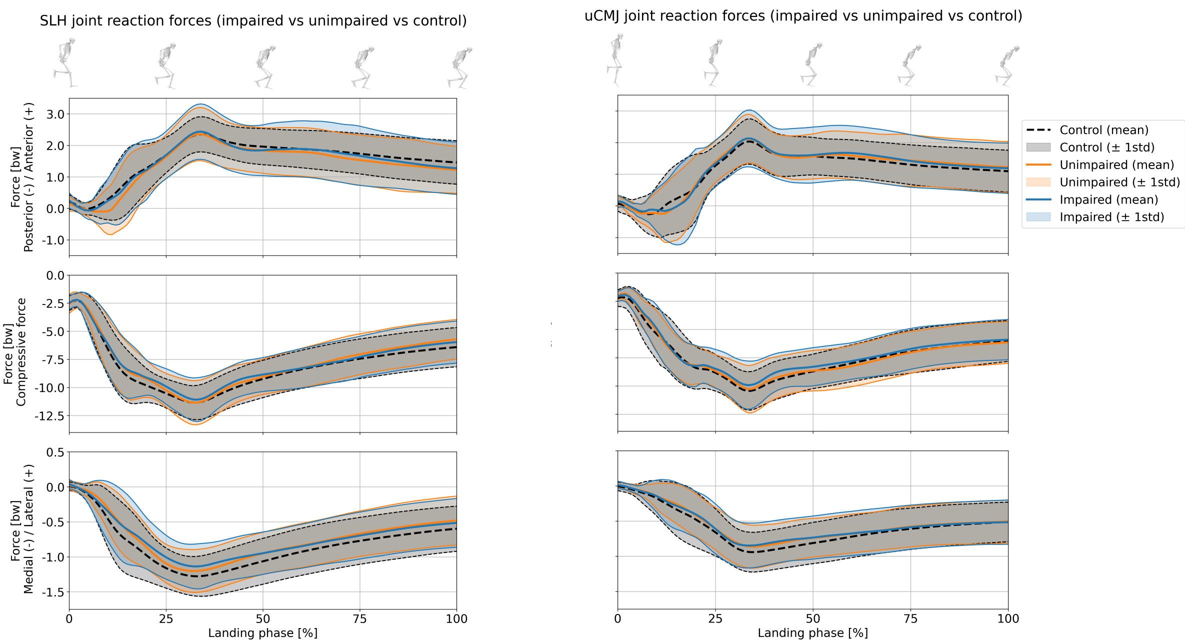


Figure 3.2: The individual (AP, ML, and compressive) JRFs for the impaired (blue), unimpaired (orange), and control (black) groups, during the SLH (a) and uCMJ (b) expressed in the tibia frame.

3.3.4. Joint angles

Knee flexion angle followed a similar pattern across all groups for both tasks (Figure 3.3). At the time of ACL peak loading during the SLH, the impaired and unimpaired groups showed lower knee flexion angle compared to the control group, with values of approximately $63°$, compared to $66°$ in controls. For the uCMJ, this value was lower, around the $61°$. The SPM analysis revealed no significant difference between the groups. Little to no difference was observed in the hip and ankle angles during both tasks.

3.3.5. Ground reaction forces

The vertical GRF component had a sharp rise following IC and peak values around the $2,3bw$ (Figure 3.4). The peak occurred earlier in the landing phase (approximately 20%) then the peak of the ACL load (33.3%). ML force showed a more notable difference between the two tasks: during the

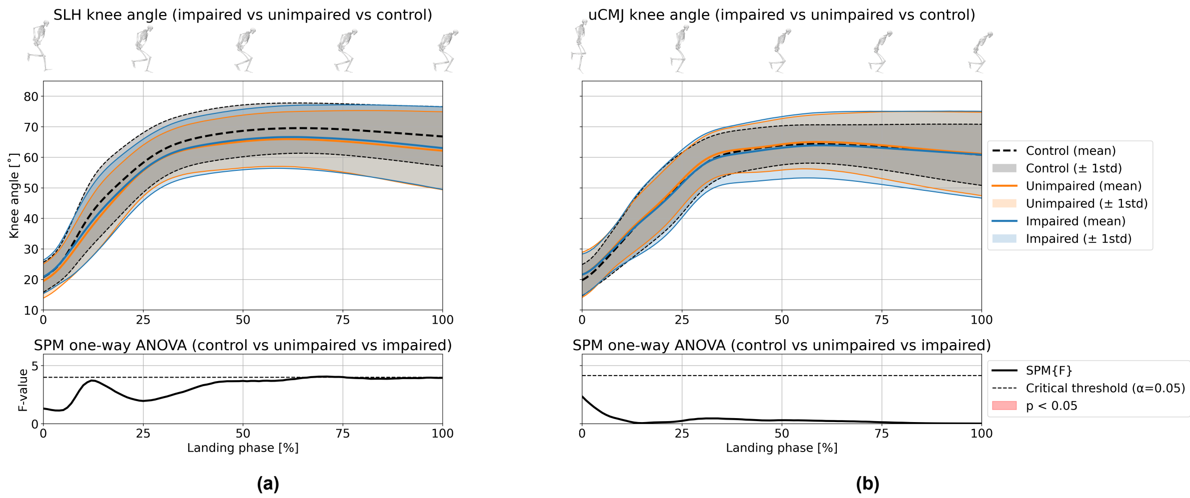


Figure 3.3: Knee angle during SLH (a) and uCMJ (b) for the impaired (blue), unimpaired (orange), and control (black) groups.

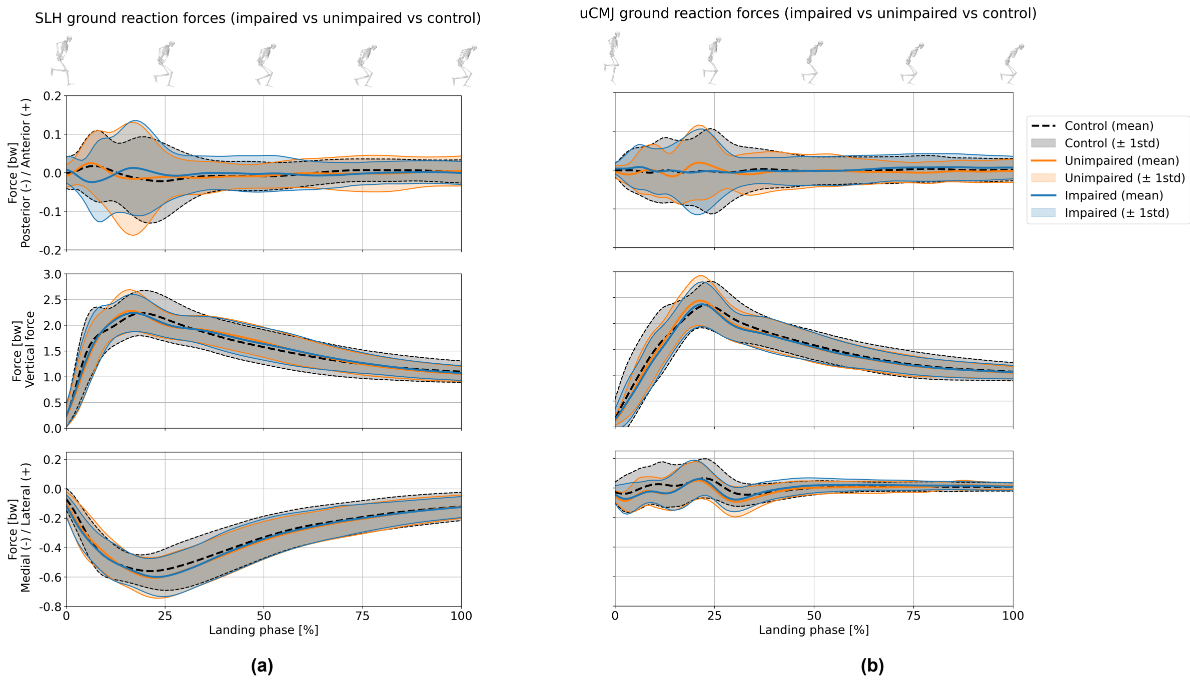


Figure 3.4: The individual (AP, ML, and compressive) GRFs for the impaired (blue), unimpaired (orange), and control (black) groups, during the SLH (a) and uCMJ (b) expressed in the tibia frame.

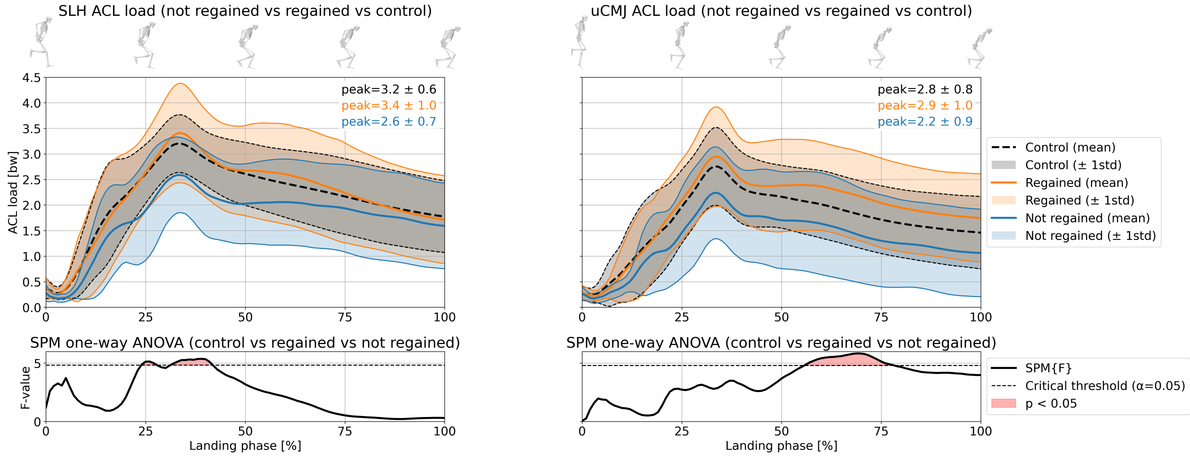
SLH it had a larger medial direction (approximately $0.51bw$), whereas for the uCMJ it remained more balanced between the medial and lateral direction.

The AP force of the GRF remained relatively small throughout the landing phase, with mean values staying close to zero and rarely exceeding $0.1bw$ in either direction across all groups.

3.4. Not regained vs regained

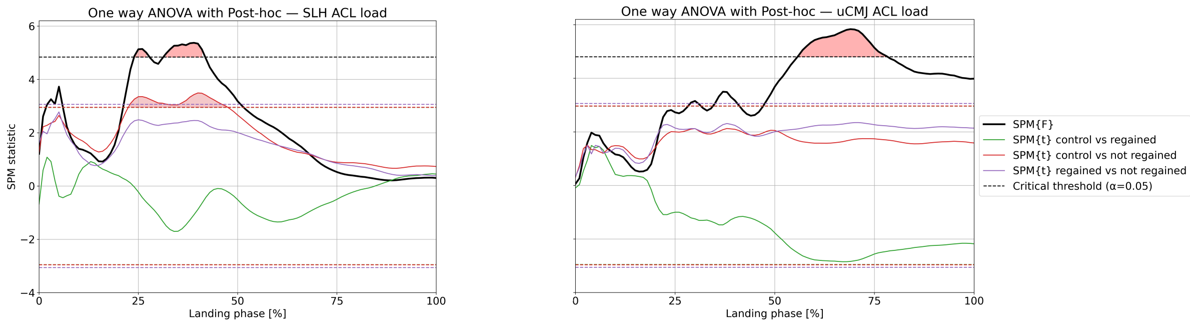
3.4.1. Timing of ACL peak

The absolute timing of the ACL peak was similar across all three groups during the SLH ($0.13s$). In contrast, differences between groups were observed during the uCMJ. The not regained group showed a peak timing comparable to that observed in the SLH, whereas the regained and control groups reached their peak sooner, at approximately $0.21s$ and $0.16s$, respectively.



(a) (b)

Figure 3.5: The ACL load (top) during the landing phase for the SLH (a) and uCMJ (b) of the not regained (blue), regained (orange), and control (black) groups. The bottom figure shows the result of the one-way ANOVA.



(a) (b)

Figure 3.6: One-way ANOVA with post hoc analysis which evaluates the significant difference between each group possibility.

3.4.2. ACL peak load

During the SLH, the overall shape of the ACL load profiles was similar across groups. However, differences were observed in peak magnitude. The not regained group showed the lowest peak load ($2.6bw$), approximately $0.6bw$ lower than the control group (Figure 3.5). The regained group showed a slightly higher peak ($3.5bw$) than the control group. The one-way ANOVA revealed significant differences around 25% and between $30 - 40\%$ of the landing phase. Post-hoc analysis indicated that these differences were present between the control and not regained groups (Figure 3.6a).

A similar pattern in peak loading was observed during the uCMJ. The regained group showed the highest peak load ($3.1bw$), followed by the control group ($2.8bw$), while the not regained group ($2.3bw$) again showed the lowest value. The difference between the regained and control groups was smaller than in the SLH (approximately $0.1bw$). The not regained group remained approximately $0.6bw$ below the control group. Additionally, the one-way ANOVA showed a significant difference between $60-75\%$ of the landing phase. However, post-hoc analysis did not identify significant differences between specific group pairs (Figure 3.6b).

3.4.3. Joint reaction forces

Similar to the impaired versus unimpaired comparison, the AP force showed the closest relationship to the ACL load profile among the three JRF components (Figure 3.7). In both the SLH and uCMJ the not regained group showed the lowest value in all three components (AP, compressive, and ML) at time of ACL peak loading. Reaching $2bw$ and $1.7bw$ for the AP, $-9.62bw$ and $-9.3bw$ for the compressive, and $-0.91bw$ and $-0.73bw$ for the ML. The differences between groups were within a similar range across tasks, approximately $0.5bw$ for the AP force, $0.7 - 0.9bw$ for the compressive force, and $0.2 - 0.3bw$ for the ML force.

Regarding the AP force profile, a posteriorly oriented force was observed shortly after initial contact in both tasks. In the SLH, this posterior phase was brief, while in the uCMJ it continued until approximately 20% of the landing phase.

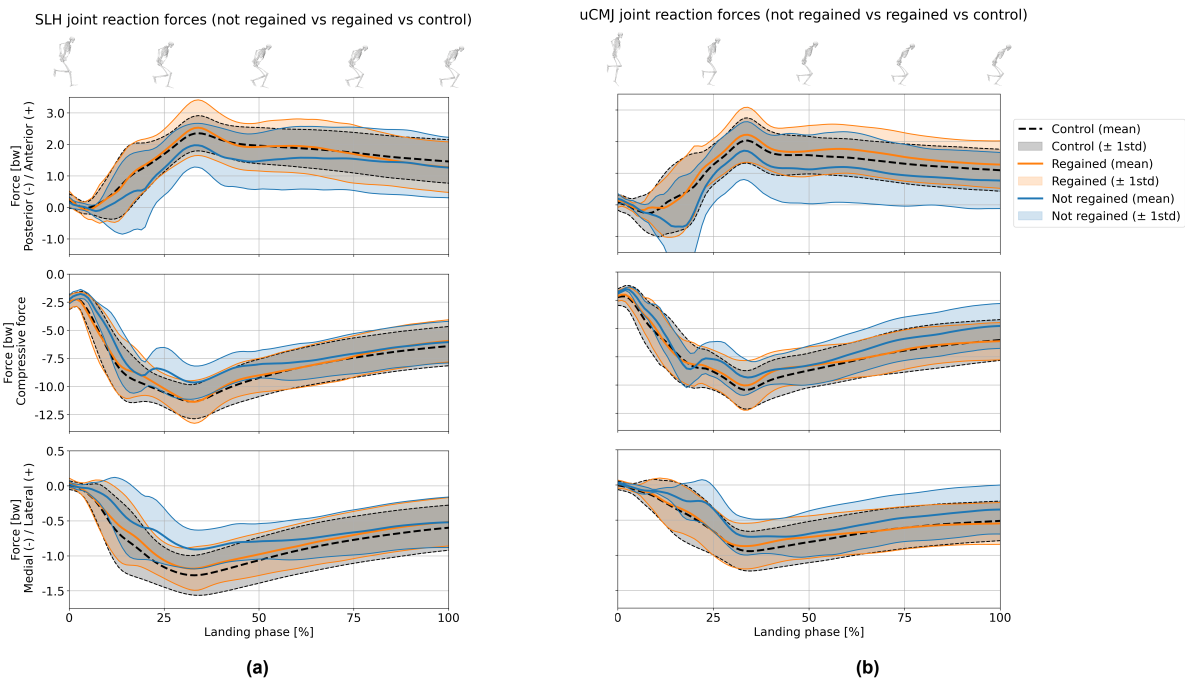


Figure 3.7: The individual (AP, ML, and compressive) JRFs for the not regained (blue), regained (orange), and control (black) groups, during the SLH (a) and uCMJ (b) expressed in the tibia frame.

3.4.4. Joint angles

For both the SLH and uCMJ tasks, the not regained group showed the lowest knee flexion angles at time of ACL peak, $59.2°$ and $54.8°$ respectively. In the SLH, this difference was mainly present in the first 50% of the landing phase. Also, a difference was observed in the uCMJ (approximately $7°$ compared to the control and regained groups), and this was consistent throughout the landing phase (Figure 3.8). However, no statistically significant differences were found in either task. In addition, both tasks showed a lower hip flexion angle at the time of peak ACL loading in the not regained group, with the not regained group reaching $50.4°$ (SLH) and $57.5°$ (uCMJ).

3.4.5. Ground reaction forces

In the SLH, the not regained group showed a less steep increase in the vertical GRF leading up to the moment of peak ACL loading compared to the control and regained groups. The peak of each group was slightly earlier (20%) than the ACL peak load (33.3%), and remained roughly the same (approximately $2.2bw$). A similar pattern was observed in the ML force, while the peaks. After this phase, both force profiles followed trends comparable to those of the other groups (Figure 3.9). This pattern was not present in the uCMJ. However, the not regained group showed a slightly higher peak ($2.7bw$) in the vertical GRF compared to the control and regained groups ($2.3bw$). The remainder of the profiles were largely similar across all groups, and to those of the SLH.

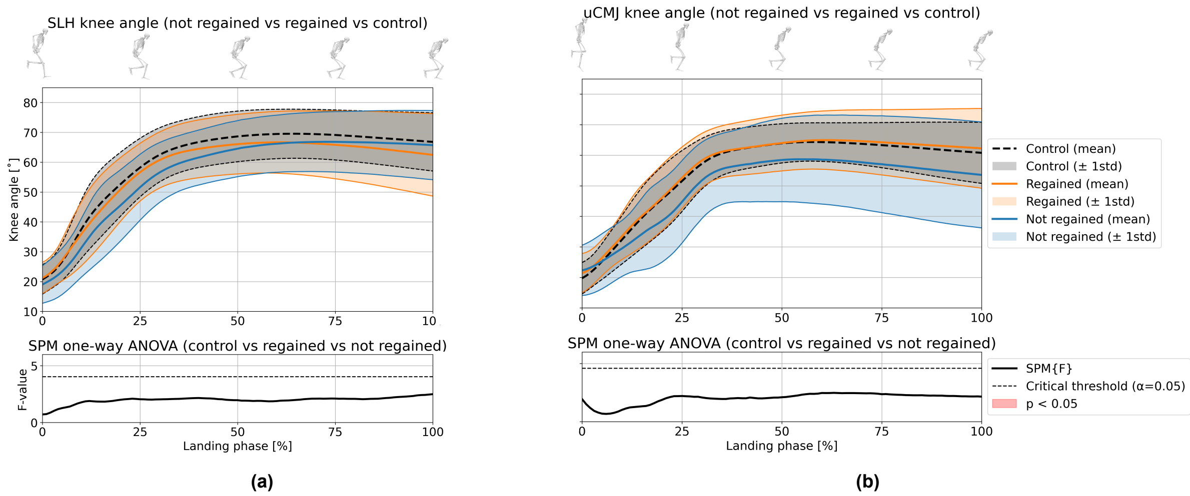


Figure 3.8: Knee angle during SLH (a) and uCMJ (b) for the not regained (blue), regained (orange), and control (black) groups.

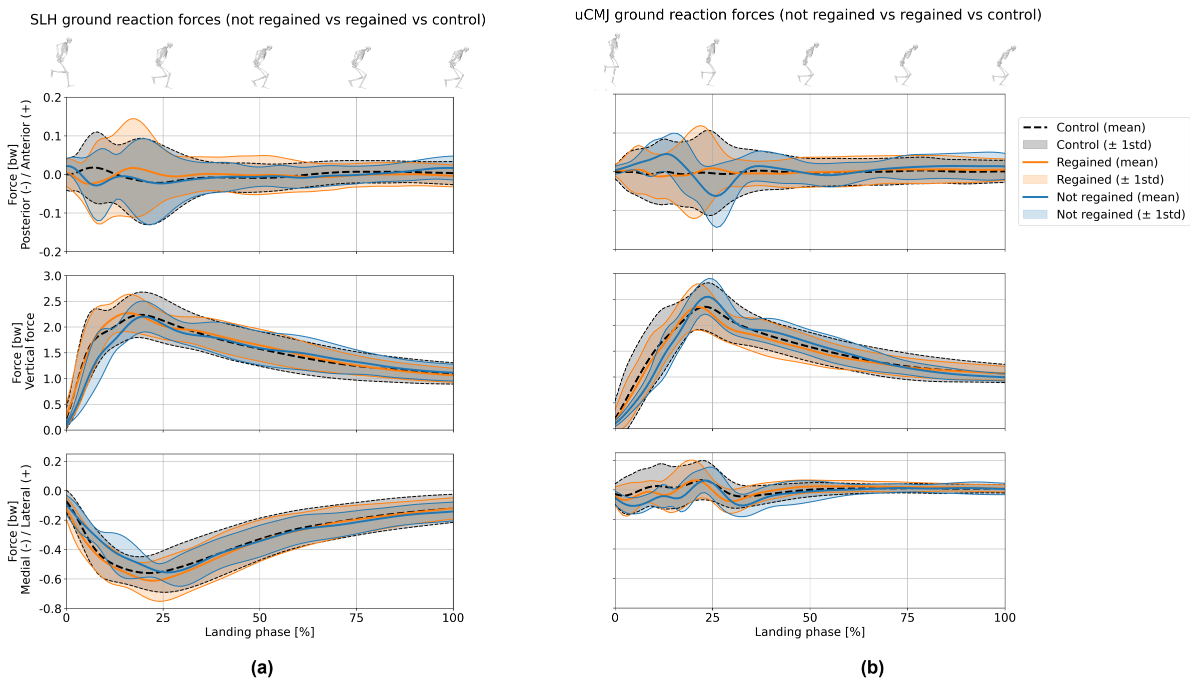


Figure 3.9: The individual (AP, ML, and compressive) GRFs for the not regained (blue), regained (orange), and control (black) groups, during the SLH (a) and uCMJ (b) expressed in the tibia frame.

Table 3.1: Summary of the biomechanical outcome measures (mean ± SD) for SLH across all groups.

	Impaired	Unimpaired	Control	Regained	Not regained
ACL:					
Absolute time peak [s]	0.13 ± 0.1	0.12 ± 0.0	0.13 ± 0.1	0.13 ± 0.1	0.12 ± 0.0
Peak load [bw]	3.31 ± 1.0	3.26 ± 0.9	3.24 ± 0.6	3.46 ± 1.0	2.60 ± 0.8
JRF forces [bw]:					
AP at ACL peak	2.48 ± 0.9	2.39 ± 0.9	2.39 ± 0.6	2.57 ± 0.9	2.00 ± 0.8
Compressive at peak	-11.07 ± 2.0	-11.38 ± 2.0	-11.35 ± 1.5	-11.36 ± 2.0	-9.62 ± 1.5
ML at peak	-1.13 ± 0.3	-1.21 ± 0.3	-1.29 ± 0.3	-1.18 ± 0.3	-0.91 ± 0.3
Angle [°]:					
Hip at IC	42.22 ± 7.2	41.44 ± 8.9	43.90 ± 9.1	42.57 ± 7.7	40.48 ± 3.9
Hip at peak	58.31 ± 8.8	56.13 ± 9.0	61.30 ± 10.6	58.47 ± 9.4	57.46 ± 4.9
Knee at IC	20.85 ± 5.5	19.46 ± 5.6	20.72 ± 4.9	21.22 ± 5.3	19.01 ± 6.7
Knee at peak	62.23 ± 10.1	61.79 ± 8.3	64.79 ± 9.4	62.83 ± 10.0	59.21 ± 10.9
Ankle at IC	-17.89 ± 16.4	-15.08 ± 16.7	-9.63 ± 17.2	-18.08 ± 15.6	-16.93 ± 21.0
Ankle at peak	8.76 ± 7.6	9.06 ± 6.1	12.37 ± 8.2	8.72 ± 8.1	8.98 ± 4.4
GRF forces [bw]:					
AP at peak	-3.72e-03 ± 4.6e-02	-1.30e-02 ± 4.3e-02	-8.69e-03 ± 5.1e-02	-2.04e-03 ± 4.6e-02	-1.21e-02 ± 4.7e-02
Vertical at peak	1.90 ± 0.3	1.93 ± 0.3	1.89 ± 0.4	1.91 ± 0.3	1.82 ± 0.3
ML at peak	-0.51 ± 0.2	-0.52 ± 0.1	-0.48 ± 0.2	-0.51 ± 0.2	-0.50 ± 0.1

Table 3.2: Summary of the biomechanical outcome measures (mean ± SD) for uCMJ across all groups.

	Impaired	Unimpaired	Control	Regained	Not regained
ACL:					
Absolute time peak [s]	0.19 ± 0.1	0.18 ± 0.1	0.16 ± 0.1	0.21 ± 0.1	0.13 ± 0.0
Peak load [bw]	2.98 ± 1.0	3.03 ± 0.9	2.84 ± 0.7	3.12 ± 0.9	2.25 ± 1.0
JRF forces [bw]:					
AP at peak	2.27 ± 0.9	2.27 ± 0.8	2.12 ± 0.7	2.38 ± 0.8	1.72 ± 1.0
Compressive at peak	-10.06 ± 2.1	-10.42 ± 2.0	-10.46 ± 1.7	-10.21 ± 2.1	-9.32 ± 1.7
ML at peak	-0.88 ± 0.3	-0.89 ± 0.3	-0.95 ± 0.3	-0.91 ± 0.3	-0.73 ± 0.3
Angle [°]:					
Hip at IC	29.43 ± 8.4	30.24 ± 9.4	29.04 ± 9.7	29.47 ± 8.6	29.21 ± 7.8
Hip at peak	56.13 ± 10.4	55.56 ± 10.9	55.14 ± 12.1	57.24 ± 10.4	50.44 ± 8.6
Knee at IC	21.54 ± 6.8	21.49 ± 7.5	19.74 ± 5.2	21.39 ± 6.5	22.32 ± 8.7
Knee at peak	61.38 ± 10.1	62.51 ± 8.7	60.53 ± 8.1	62.66 ± 9.2	54.80 ± 12.4
Ankle at IC	-25.86 ± 11.9	-26.94 ± 9.3	-22.98 ± 14.8	-25.60 ± 12.7	-27.21 ± 6.6
Ankle at peak	21.68 ± 5.0	22.96 ± 5.8	23.27 ± 5.6	21.90 ± 5.3	20.58 ± 2.8
GRF forces [bw]:					
AP at peak	-5.36e-04 ± 3.1e-02	-1.44e-02 ± 5.3e-02	-2.06e-04 ± 5.8e-02	-1.67e-03 ± 3.0e-02	5.27e-03 ± 3.9e-02
Vertical at peak	1.80 ± 0.4	1.84 ± 0.4	1.93 ± 0.4	1.77 ± 0.4	1.94 ± 0.2
ML at peak	-5.52e-02 ± 8.3e-02	-7.56e-02 ± 9.2e-02	-4.52e-02 ± 7.4e-02	-4.50e-02 ± 8.1e-02	-0.11 ± 0.1

4 Discussion

4.1. General

The aim of this study was to compare ACL loading and lower limb kinematics across two separate comparisons: the impaired versus unimpaired leg, and participants who had and had not regained to their pre-injury sport activity level following ACLR. Two functional tasks were assessed: SLH and uCMJ. Overall, no significant differences were found between the impaired, unimpaired, and control group for either task, suggesting that the ACL-reconstructed participants had largely recovered to a functional level comparable to that of healthy controls at the time of testing. However, when comparing participants who had and had not regained their pre-activity level, a significant difference in ACL peak load was found during the SLH, where post-hoc analysis confirmed this difference between the control and not regained groups. During the uCMJ, a significant difference was also found by the one-way ANOVA, though post-hoc analysis did not identify significant differences between specific group pairs.

4.2. Result validation

This study quantified and compared ACL loading during the SLH and uCMJ in ACLR-rehabilitated athletes using musculoskeletal modeling and a vector-projection approach to estimate ACL force. The analysis pipeline provided a practical and reproducible way to estimate ACL loading in a clinical research setting, without requiring subject-specific imaging or invasive measurements. Validating the obtained ACL loads is difficult due to the absence of a golden standard. However, by looking at in literature reported outcome, the confidence of these findings can be established.

4.2.1. ACL load magnitude

The ACL peak loads reported in this study were higher than the $0.5 - 1.7bw$ reported in gait analysis studies [24, 35–38]. This was expected given the more dynamic and demanding nature of these jump-landing tasks investigated in this study. When comparing functional tasks, uCMJ values fell within the range reported by Chen et al. [25], whereas SLH loads were $0.5 - 0.7bw$ higher. A similar trend was observed when comparing to Kar et al. [23], with values in the present study exceeding theirs by $0.3 - 1.2bw$. Both studies examined drop jumps in female athletes. Given the relatively similar nature of these tasks with the tasks conducted in the present study, it was expected that the values, especially of the SLH, were closer to the in literature reported values.

A potential reason of this overestimation could lie within the methodology. The ACL was modeled as a single bundle oriented along a straight-line path between its origin and insertion. This was then used in the vector projection, neglecting other ligaments. However the MCL has been reported to play a small but significant role in resisting anterior tibial translation [39]. Additionally, studies have found that a medial meniscetomy leads to an increased anterior translation, especially in the ACL-deficient knee [40]. Neglecting the load-sharing role of secondary stabilizers such as the MCL and meniscus, may lead to a slight overestimation of ACL force.

Furthermore, while SO is computationally efficient, the cost function calculates a solution at every timestep independently, excluding the possibility of using time-integral criteria. This approach can result in unrealistic muscle force estimates [41]. This directly affects ACL load estimates, as the JRF is primarily determined by muscle forces rather than the GRF. This is supported by the results, where the compressive JRF exceeded $10bw$, while the vertical GRF was approximately five times lower. Together, both the absence of ligament load-sharing and the unrealistic estimation of muscle forces by SO are likely to have contributed to the higher ACL loads observed in this study compared to values reported in the literature.

4.2.2. Muscle forces

The estimated muscle contributions showed a trend similar to that reported by Kotsifaki et al. [14], with the quadriceps being the dominant contributor to knee joint loading. This is in line with existing literature, where the quadriceps are identified as a primary contributor to anterior tibial shear and, consequently, ACL loading [42, 43].

A notable difference with the literature was the higher activation of the soleus in the current study. This may be explained by differences in the muscle force estimation approach. The present study relied on SO without electromyography (EMG) constraints, whereas EMG-informed approaches can better capture subject-specific muscle activation patterns. As a result, the optimization procedure may have redistributed load toward the soleus to satisfy joint moment requirements, potentially overestimating its contribution.

4.2.3. ACL peak timing

Furthermore, the timing of ACL peak loading was consistent with findings by Peel et al. [22], who reported that peak ACL forces occur shortly after initial contact during landing tasks. In the present study, this early peak was observed for both the SLH and uCMJ. The SLH demonstrated on average an earlier peak compared to the uCMJ, which may be related to the more demanding horizontal landing mechanics of the SLH.

4.2.4. Observed posterior force

Across all tasks it was observed that the AP force was going into the posterior direction right after IGC. This predominantly present in the not regained group during the uCMJ. Posterior tibial shear forces are often seen when the hamstrings and soleus are active, as they reduce ACL loading by generating posterior tibial shear force [3, 44]. The hamstrings only have this effect when the knee is flexed more than $20°$ to $30°$ [44]. While the soleus was active during the landing phase, the hamstrings was barely. The presence of a posterior force around IGC in the current study may therefore be an artifact of the prescribed 1DoF knee joint model rather than a true physiological phenomenon. It should be noted that the posterior force did not appear in the final ACL loading output for two reasons: (1) only anterior AP forces were considered in the ACL load calculation, and (2) the added indirect AP force counteracted the effect largely.

4.2.5. Overall plausibility

Additionally, Beaulieu et al. reported that for knee angles higher than $30°$ the ACL resists approximately $62 - 85\%$ of the anterior shear force [3]. As a check on plausibility, the ratio of the estimated ACL peak load to the total anterior shear force acting on the knee was computed. The total anterior shear force was defined as the sum of the direct AP component of the JRF and the indirect AP contribution derived from the tibial slope (Equation 2.3), representing the full anterior shear demand that passive stabilizers must resist. Dividing the estimated ACL peak load by this combined value yields values of 84% and 79% for the SLH and uCMJ respectively across all comparisons, both of which fall within this reported range. This suggests that, despite a possible overestimation of the absolute values, the relative load distribution at the knee remains physiologically plausible.

Since Equation 2.3 is a linear function, the sensitivity of the indirect AP contribution to variations in tibial slope can be directly assessed. For a tibial slope angle of $7.3°$, the indirect contribution accounts for approximately 12.8% of the compressive force. This value is slightly lower but still consistent of the reported value of 16% by Yeow et al. [45].

4.3. Impaired versus unimpaired

Contrary to expectations, no significant differences in ACL peak load, JRFs, or knee kinematics were found between the impaired and unimpaired limbs, or between either group or healthy controls. If a difference was seen it was expected that this was caused by a difference in GRF and knee joint flexion angles. As these differences were not observed, it can be concluded that the participants had recovered to a level comparable to healthy controls at the time of testing.

The absence of asymmetry between the impaired, unimpaired, and control group is likely related to the time since injury. Participants were tested approximately 4 years post-injury, which is later than the typical RTS timeframe [10, 11, 16, 46]. It is therefore possible that any compensatory movement strategies that were present earlier in rehabilitation had already resolved, allowing the impaired leg to function comparably to the unimpaired leg.

It can additionally be explained by the jump protocol. In the protocol the jump distance is standardized by taking the full leg length of the participant, therefore making it a submaximal effort jump. As a result, the task may not be challenging enough for the reconstructed ACL to reveal remaining loading asymmetries between limbs.

4.4. Not regained versus regained

For both tasks the one-way ANOVA revealed a significant difference in ACL loads. Only for the SLH the post-hoc analysis showed that the not regained group had a significant lower mean than the control group. The uCMJ showed a similar pattern, with the not regained group having the lowest peak value, however, this was not significant. These lower ACL peak loads suggest that the knee is not yet fully loaded in this group, which may explain why these athletes have not returned to their pre-injury activity level. A few explanations may explain this finding.

The first explanation is a deliberate unloading strategy. Unloading strategies are often associated with higher loading in the unimpaired limb and asymmetries in joint angles [15, 47, 48]. While a direct comparison with the unimpaired limb was not performed in this analysis, this pattern is consistent with previously reported asymmetrical loading strategies. It could be hypothesized that if the unimpaired limb carries a greater share of the load, a reduction in loading of the impaired limb would be expected. This is supported by the lower JRFs observed in the not regained group compared to the control group. Baumgart et al. described a compensation strategy whereby participants reduce the vertical GRF component [49]. However, in the present study no clear reduction in the vertical GRF was observed. Instead, a less steep increase in the vertical GRF leading up to peak ACL loading was found, which may reflect a more cautious rate of loading. This is supported by the lower knee angles leading up to ACL peak loading at both tasks.

Additionally, the not regained group showed a lower knee flexion angle throughout most of the landing phase, most notably during the uCMJ (approximately $7°$ compared to the other groups). This more extended knee position has two contributing effects on the estimated ACL load. First, it affects the orientation of the ACL vector, as this is related to the knee flexion angle through the attachment sites. This reduces the scalar projection of the JRF onto the ACL, and therefore also the estimated ACL load. This may partly explain the lower ACL peak loads observed in the not regained group, independent of any loading strategy. Second, with a more extended knee the quadriceps operate at a less favorable moment arm, reducing the muscular demand required to control the landing [25]. Since muscle forces are the dominant contributor to the estimated JRF, this reduced quadriceps loading directly results in a lower JRF, which in turn reflects into a lower estimated ACL load. Both effects may therefore partly explain the lower ACL peak loads observed in the not regained group, independent of any loading strategy.

While all explanations are consistent with the presence of a compensatory loading strategy, the difference in knee kinematics yielded no significant differences. Therefore, the results are not conclusive regarding the presence of a compensation strategy. To better assess this, joint moments should also be analyzed, as they provide additional insight into muscle-driven loading strategies that are not fully captured by JRFs and kinematics alone.

Interestingly, the not regained group had a shorter mean time since injury compared to the regained group. Since the not regained group shows either a significant or lower trend in ACL peak load, this suggest that a follow up closer to the injury shows a difference. However, more importantly, this conclusion cannot be drawn due to the inhomogeneous characteristics between the two groups.

4.5. Functional task effectiveness

Across all comparisons, the SLH produced higher peak ACL loads than the uCMJ, which is consistent with the more dynamic landing mechanics of the SLH [14]. This can be explained due to the fact that during the uCMJ a more extended knee was observed. As earlier discussed this leads to a more vertical ACL vector, making the anterior shear force component less powerful in the vector analysis.

Additionally, the higher task demand also appears to result in greater sensitivity for detecting between-group differences. A significant difference in ACL peak load was found between the regained, not regained, and control groups during the SLH, with post-hoc analysis confirming this between the control and not regained groups. This is in line with the findings of Kotsifaki et al. [14, 15], who showed that kinematic and kinetic asymmetries can be detected during the SLH and triple hop for distance when biomechanical analysis is used instead of performance-based metrics such as LSI. This suggests that the SLH is capable of distinguishing between groups with different levels of recovery when analyzed beyond outcome measures alone.

The difference in landing mechanics between the two tasks is also shown in the ML component of the GRF. During the SLH, a larger medial ML force was found compared to the uCMJ. This indicates that participants tended to land with the knee directed more inwards during the SLH. This is likely related to the horizontal nature of the SLH landing, where the forward momentum may contribute to a more medially directed landing position. In contrast, the uCMJ showed no clear pattern in the ML direction. The force values were closer to zero and showed greater variation between participants. Since the uCMJ is primarily a vertical jump, there is no preferred landing direction, which may explain the more variable ML force profile. Overall, these findings show that the two tasks place different mechanical demands on the lower limb, which should be considered when selecting functional tests for clinical RTS assessment.

It should be noted that in the present study, the SLH was not performed at maximal effort. Participants were instructed to land at a fixed distance of 100% of leg length rather than hopping for maximum distance. Despite this, the SLH still produced higher ACL peak loads than the uCMJ and revealed a statistically significant group difference. When a maximal SLH test is performed it is expected that the differences are even bigger, suggesting that the current findings may underestimate how well the SLH can distinguish between athletes at different stages of recovery. Nevertheless, it suggests that even a submaximal SLH is sufficiently demanding to expose differences in ACL loading between athletes at different stages of recovery. This further underlines its value as a clinical assessment tool.

4.6. Limitation and future research

These findings should, however, be interpreted with caution. A key limitation of the return-to-pre-injury activity comparison is the considerable imbalance in sample size between the not regained (n = 3), regained (n = 16), and control (n = 20) groups. With only three participants in the not regained group, the statistical power of between-group comparisons is limited, and therefore, limits the interpretability of the results. The significant difference in SLH ACL peak load may represent a true finding, however this cannot be concluded with most certainty due to inhomogeneous group comparison. This difference is explicitly noticeable in weight ($76.7kg$ versus $68.0kg$), BMI ($24.2kg/m^2$ versus $22.3kg/m^2$)), and the time since injury (2.3 years versus 4.1 years). Therefore, the significant difference in SLH ACL peak load and the kinematic differences in uCMJ knee angle are potentially meaningful findings, but require replication in a larger more homogeneous cohort.

It should also be considered that the observed differences in ACL peak load at the not regained vs regained comparison may be partially influenced by the jump protocol itself. Participants were instructed to land at a fixed distance of 100% of their leg length rather than hopping for maximum distance. This means that participants with greater athletic capacity, such as those in the regained group, were not necessarily performing at maximal effort, and the not regained group may have found the fixed distance relatively more demanding. This hypothesis is backed by the fact that the the BMI of the not regained group is slightly higher than the regained group. As a result, the difference in ACL peak load between groups could reflect differences in relative effort rather than a true difference in loading strategy. Future studies should consider a maximal-effort SLH protocol to better isolate group differences in ACL loading from protocol-related confounds.

The long follow-up period 3.8 means that these findings may not apply to athletes tested at the typical RTS clearance time, when movement deficits are more likely to be present [50]. It is likely that in this study the compensatory strategies of the participants had resolved. This would allow the reconstructed limb to function comparably to the uninjured limb and to healthy controls. This interpretation is supported by the absence of compensatory kinematic strategies in the present study. Therefore, a cohort tested closer to the time of RTS clearance would be needed to determine whether symmetry in ACL loading is achieved at that stage.

Additionally, the Catelli model contains a 1DoF knee, which has as an important limitation: AP translation is constrained by flexion angle rather than being governed by ligament mechanics. This prevents the model from independently capturing tibial translation in response to dynamic load. This can limit the physiological accuracy of the estimated joint forces, and can be an explanation of the observed posterior force. In contrast, higher degrees of freedom knees with modeled ligaments (including the ACL), overcome this limitation and are better suited for directly estimating the ACL loading [18, 19]. However they are mostly patient specific and computationally more demanding [20].

An intermediate step towards a full ligament-driven model would be the adoption of a 3DoF knee, which would allow for independent motion in the sagittal, frontal, and transverse planes and provide a more physiologically representative estimation of knee joint mechanics without the full complexity of explicit ligament modeling [51]. Reproducing this study with a model with integrated 3DoF knee model would be highly encouraged, and is expected to better capture the loading behavior of the ACL during the SLH and uCMJ.

Furthermore, no EMG data was incorporated in this study, which limits the ability to assess muscle activation patterns during both tasks. This would have been beneficial by using a EMG-driven SO, and for validation purposes. However, since the found database had no incorporated this could not have been realized. It is suggested that when these results will be reproduced or elaborated on, EMG will be implemented.

As mentioned in subsection 4.2.1, the SO has a disadvantage with regards to the muscle force estimation. A more physiologically accurate optimizer is computed muscle control (CMC),which incorporates muscle activation dynamics by integrating over previously solved time steps [52]. However, this makes CMC considerably more computationally demanding, which limits its feasibility for larger datasets such as the one used in this study. An intermediate alternative is the Rapid Muscle Redundancy (RMR) solver [53]. Similar to SO, the RMR solver is computationally efficient, solving the muscle redundancy problem at each time step independently. However, unlike SO, it incorporates additional constraints on muscle activation continuity and passive fiber forces, resulting in more physiologically representative muscle force estimates. Utilizing the RMR solver in future research would therefore improve the accuracy of the ACL load estimates in large cohort studies.

The ACL attachment coordinates used in this study are another important factor to mention. The origin and insertion points were taken from a healthy native ACL, as reported by Stanev et al. [32], since subject-specific graft geometry was not available in this dataset. In ACLR patients, graft placement varies depending on surgical technique, graft type, and individual anatomy [54]. As a result, the actual ACL vector orientation may differ from the one assumed in this study. The direction of this error is difficult to determine without subject-specific imaging. However, differences between native and reconstructed ACL geometry may introduce a systematic bias in the estimated ACL load, especially in the direction and magnitude of the vector projection.

It should also be noted that the original intention of this study was to include participants who were still actively undergoing ACL reconstruction rehabilitation. Due to practical limitations, however, the final sample consisted of individuals who had already completed rehabilitation, which may partly explain the small differences observed between groups. The subtle but significant difference in ACL peak load found in the not regained group during the SLH nonetheless emphasizes the question of how ACL loading patterns present in participants who are still working towards return to sport. Future studies should therefore prioritize recruiting participants at earlier stages of rehabilitation to better capture these differences.

4.7. Methodological evaluation

The musculoskeletal modeling approach used in this study offers several practical advantages. The pipeline is computationally efficient, allowing for the processing of large datasets without the need for subject-specific imaging or instrumented implants. Furthermore, the use of a generic scaled model makes the approach accessible and reproducible across research settings. These characteristics make it a suitable tool for estimating ACL loading in a clinical research context, provided its limitations are taken into account.

To the best of the author's knowledge, the pipeline presented in this study, combining neuromusculoskeletal modeling with a vector-based ACL load estimation approach during functional RTS tasks in a larger cohort of ACLR-rehabilitated athletes, has not been previously reported in the literature. It requires standard motion capture and force plate data, which is increasingly available in clinical and sports science settings. Since it does not require the need of subject-specific imaging, it is applicable towards a broad clinical setting. However, translating this approach into a routine clinical practice would require solving some of the limitations described above.

The most impactful improvement would be to tackle the overestimated values of the ACL load, to make them more representative for realistic values. This should be addressed by improving the knee model and the optimization algorithm used, as these do not require additional data collection aside from the already needed motion capture and force plate recordings. Another benefit of using a more physiologically representative knee model, would mean that artifacts such as the posteriorly observed JRF will be minimized.

However, when MRI or CT is available, the accuracy of the approach can be enhanced by specifying the graft attachment sites. This would translate in a more representative ACL vector. Additionally the tibial slope can be extracted, replacing the population mean value currently used in the indirect AP force contribution calculation. While these imaging-based improvements would reflect a more realistic ACL load estimation based on the participant, it is not always available, and should therefore be less prioritized when making this approach suitable for assessments in the clinic.

5

Conclusion

This study quantified and compared anterior cruciate ligament (ACL) loading during the single leg hop for distance (SLH) and unilateral countermovement jump (uCMJ) in ACL reconstructed (ACLR) rehabilitated athletes using musculoskeletal modeling and a vector-projection approach to estimate ACL load.

No significant differences in ACL peak load, joint reaction forces (JRFs), ground reaction forces (GRFs), or knee kinematics were found between the impaired and unimpaired limbs, or between the ACLR group and healthy controls. This suggests that participants had recovered to a level comparable to healthy individuals at the time of testing. This is likely related to the long follow-up period of approximately 3.8 years, which exceeds the typical RTS clearance timeframe. It should be noted that the distance standardization of 100% leg length making it a submaximal jump, may have limited the ability to detect remaining asymmetries.

When comparing participants who had and had not returned to their pre-injury sport level, a significant difference between the control and not regained group was identified during the SLH. The not regained group showed the lowest peak load at both tasks, suggesting a more cautious loading strategy. This could be explained by a deliberate unloading strategy reflected by a more cautious rate of loading, and the effect of a more extended knee posture, which reduces both the quadriceps muscular demand and the scalar projection of the JRF onto the ACL vector.

Participants who had returned to sport showed, JRFs, GRFs, and knee kinematics that were more similar to those of the control group, suggesting more typical movement patterns. However, it cannot be concluded that pre-injury movement mechanics were fully restored.

Across both tasks, the SLH resulted in higher peak ACL loads than the uCMJ and appeared more sensitive to detecting significant differences between groups. This supports its use as a clinically relevant task, even when performed under submaximal conditions. However, a maximal effort protocol is preferred, as this is expected to yield greater differences between athletes.

By demonstrating that the ACL load can be estimated from motion data in a reproducible and scalable way, this study opens the door to incorporate ligament load estimation into both large cohort research and RTS assessment, without the need for subject-specific imaging. Future refinements, including higher DoF knee models and EMG-informed optimization, are expected to improve that accuracy while maintaining the clinical accessibility that makes this approach valuable.

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A

Literature Review

A literature review for the course BM51010.

Kinematic and Kinetic Measures in Return-to-Sport Testing Following ACL Reconstruction: A Systematic Review

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Background: Anterior cruciate ligament rupture is a prevalent and severe injury within pivoting sport. It marks the starting point of an intense rehabilitation process where stability and function of the knee will be maximized, while minimizing re-injury. An important milestone is the return-to-sport (RTS) assessment, however the rehabilitation path to achieve this is not standardized, and thus different tests are widely used. This systematic review summarizes the tests currently used in RTS and addresses there effectiveness.
Methods: A search using PubMed and SCOPUS was performed for articles regarding RTS assessment. Using the PICOS framework the inclusion criteria were determined. For each included study the study characteristics, athlete group, RTS test, and criteria were extracted. After, a non-systematic part was written about the effectiveness of the identified tests and criteria.
Results: The search resulted in 505 studies from which fifteen were eligible to be included in the study. The identified RTS test were functional tests and subjective tests. The functional tests were categorized in hop, jump, strength, and balance test. Additionally, psychological tests were also found in the majority of the studies. Evidence showed that functional and psychological criteria combined significantly reduced re-injury risk when used within a multi-modal assessment. Including time from reconstruction minimize the risk further.
Discussion: Functional tests such as hop and jump assessments were most frequently reported, with ≥90% LSI as the dominant threshold. Psychological measures (IKDC and ACL-RSI) were consistently associated with higher RTS success rates. Despite wide use, test batteries remain non-standardized. A multi-modal, time-based approach proved most effective for minimizing graft rupture after ACL reconstruction. However, these tests primarily evaluate the lower-limb kinetic chain and do not directly assess knee or ACL-specific function, indicating a need for future research using more direct biomechanical or structural measures.

I. Introduction

A. Background

The anterior cruciate ligament (ACL; see Appendix 1 for full list of abbreviations) is a critical stabilizing structure in the knee joint that plays a fundamental role in maintaining joint integrity during dynamic movements, such as pivoting, jumping, and cutting actions that are frequently performed in high-level sports. ACL rupture are particularly prevalent among professional and elite athletes participating in sports such as football, basketball, and soccer [1].

In European professional soccer clubs, the incidence rate is approximately 0.4 per season per team [2], meaning that, approximately, a team experiences one ACL rupture every two seasons. Considering this, along with the fact that rehabilitation typically requires around 222 days [3], underscores the severity of this injury. Furthermore, ACL injuries not only compromise athletic performance, but also carry potentially career-altering consequences for professional athletes such as starting fewer games, reduced playing minutes, and shorter careers [4–8].

B. Rehabilitation process

Rehabilitation after ACL reconstruction is commonly described in the literature as a phased process, usually spanning four to nine stages [9–13], which share a broadly similar structure. Immediately after ACL reconstruction (ACLR), the rehabilitation program begins by focusing on pain management and swelling reduction.

As rehabilitation progresses, emphasis shifts toward structured strength training and improving proprioception. Eventually, sport-specific functional training, such as coordinated movement patterns and agility exercises, is introduced, tailored to the athlete to maximize stability and function while minimizing the risk of re-injury [4, 9, 11, 12]. The rehabilitation process is considered complete once the athlete successfully returns to sport (RTS).

A challenge in ACL rehabilitation is accurately determining when an athlete is ready to safely RTS. When this multi-factorial decision is premature or inadequately evaluated, the risk of re-injury increases, highlighting the importance of a robust RTS criteria [14, 15]. The RTS criteria are, however, not standardized [11, 16] and often rely on subjective and objective data [17–19]. Several studies have highlighted the need for more objective data in the decision making to help standardize the assessment [20, 21]. However, as Davies et al. also discusses [16], every athlete progresses through the process differently, making it difficult to determine one golden standard.

Despite the growing body of RTS literature, there remains limited consensus on which measures are currently used to guide RTS decision-making following ACLR. Therefore the aim of this systematic review is to get a better understanding of the different RTS assessments, and to identify what objective data is used in this decision making. This is addressed by answering the following research question: *how is RTS assessed in athletes playing at competitive level or higher post-ACLR, and what quantitative measures are used?*

II. Methods

The research question wass answered by means of systematic review according to the Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) 2020 statement [22]. A search was executed on 17th of September 2025 using MEDLINE-PubMed and Scopus (Elsevier). For the search a query was made consisting of three key elements: RTS, ACL, and activity level. Table 1 shows all three elements and their corresponding search term. Appendix 2 shows the full query used for each database.

Table 1. Key elements of the query with their respective search terms.

Key elements	Search term
RTS	("return to sport" OR ("readiness" AND "sport") OR "RTS" OR "RTP")
ACL	(Anterior cruciate ligament OR ACL)
Activity level	("professional" OR "elite" OR "high performance" OR "competitive" OR "high-level" OR "semi-professional")

Abbreviations: RTS = return to sport, RTP = return to participation
ACL = anterior cruciate ligament

A. Study selection and criteria

After the search was completed and duplicates were removed, the eligibility of the articles was assessed using the Population, Intervention, Comparison, Outcomes and Study design (PICOS) framework (Table 2). The PICOS criteria were specifically designed to align with the research question, which focuses on RTS assessment in competitive athletes post-ACLR.

The population was restricted to competitive or higher-level athletes, as RTS decision-making and performance demands differ from recreational sports participation. This increases the clinical relevance of the findings for competitive athletes. Pediatric-only populations were excluded due to physical differences, which may limit comparability with adult athletes.

The intervention criterion included post-ACLR rehabilitation studies that reported RTS-related assessments or decision-making. This ensured that only studies addressing RTS readiness were included, rather than studies reporting general rehabilitation outcomes. Interventions unrelated to RTS, or studies focusing only on technological and/or therapies without an RTS assessment, were excluded.

For comparison, studies with healthy controls, pre-injury baselines, or intra-subject comparisons were included. However, studies without a comparator were not excluded, as RTS assessments are often evaluated descriptively in applied sports settings, and excluding such studies would unnecessarily

Table 2. The PICOS framework used.

Key elements	Criteria	Description
Population (P)	Inclusion	Athletes of any gender, undergone ACL reconstruction, at competitive level or higher.
	Exclusion	Only pediatric athletes, recreational-only athletes, animal models, cadaver studies.
Intervention (I)	Inclusion	Rehabilitation post ACLR, reporting the use of tests related to RTS assessment and/or decision-making.
	Exclusion	Interventions unrelated to RTS, blood flow restriction therapy, and/or technology-based intervention without RTS assessment.
Comparison (C)	Inclusion	Healthy controls, pre-injury baseline, or intra-subject comparisons.
	Exclusion	No comparison required; studies without comparators are not excluded.
Outcomes (O)	Inclusion	RTS assessment methods, including objective test batteries and/or psychological readiness questionnaires. Studies reporting only RTS return rates were excluded.
	Exclusion	Studies reporting RTS no assessment/criteria.
Study design (S)	Inclusion	Randomized controlled trials, case reports, prospective cohort studies, retrospective cohort studies, cross-sectional studies, and case-control study.
	Exclusion	Editorials, conference abstracts, (systematic/narrative/scoping) reviews, and meta-analysis.
General	Inclusion	English-language, peer-reviewed, electronically available, free access via TU Delft.
	Exclusion	Non-English, and non-peer-reviewed.

Abbreviations: ACL = anterior cruciate ligament, ACLR = anterior cruciate ligament reconstruction, RTS = return-to-sport, TU Delft = Delft University of Technology

limit the available evidence.

Regarding outcomes, only studies reporting RTS test batteries and/or psychological readiness assessments were included, as the aim of this review was to identify and evaluate all RTS assessment methods. During screening, only articles explicitly addressing RTS assessment were considered eligible. A published consensus statement recommends separating the RTS continuum into three phases: return to participation, return to sport, and return to performance [23]. These terms are often used interchangeably, therefore, all related RTS terms were included in the search strategy. This was achieved by using MeSH terms in PubMed and comparable indexed terms in Scopus to ensure comprehensive article extractions. To ensure consistency in how RTS was interpreted across studies, the definition proposed by the Panther Symposium ACL Injury RTS Consensus Group was applied [24], which defines RTS as a return to the previous level of sport, but not necessarily at the desired or pre-injury performance level.

A broad range of study designs was accepted, including randomized controlled trials and observational studies, reflecting the limited availability of high-level experimental research in elite sport populations. Reviews, editorials, and conference abstracts were excluded to ensure inclusion of original, peer-reviewed studies with sufficient methodological detail.

The screening process consisted of two phases: title-abstract screening and full-text screening. Catchii, a free systematic review tool [25], was used to facilitate the whole screening process. Interestingly, Catchii includes an integrated artificial intelligence-driven Auto Reviewer (AR) that can help analyse in the title-abstract screening, based on the given inclusion and exclusion criteria. To enhance comprehensiveness, the AR function was used as a secondary screener to cross-validate the primary screening conducted by the researcher. The PICOS framework was used as input for AR's inclusion and exclusion criteria. Any discrepancies identified by the AR were re-evaluated by the primary reviewer, taking the AR's feedback into consideration. Thus, all final inclusion decisions were made by the primary researcher.

Once all conflicts were resolved, the process proceeded to the second phase: full-text screening. Which was conducted solely by the researcher, as the AR is not available for full-text screening. For the purpose of this study "competitive" was defined as participating in sports by training at least 3 times a week and/or athletes who score at least a 6 on the Tegner activity scale.

Studies that included both recreational and competitive athletes were excluded if the two groups underwent different assessments. Studies were included if both groups completed the same assessment, as this indicates that the test is applicable to competitive athletes, which directly addresses the research question.

The final set of included articles was then used for data extraction.

B. Data extraction and analysis

Following the selection process, data from all included studies were extracted using predefined data extraction criteria. The data extraction criteria are as follows:

1) Publication characteristics: First author, year of publication, and country.
2) Study characteristics: Study design and sample size.
3) Participant characteristics: Sport type, competitive level, age, gender, and graft type.
4) RTS assessment methods: Objective functional tests (hop, jump, strength, balance), subjective questionnaires (e.g., IKDC, ACL-RSI, Lysholm, KOOS), and clinical measures (e.g., knee effusion, range of motion, pain, stability tests).
5) Outcome metrics: Quantitative measures such as limb symmetry index (LSI), peak torque, jump height, reactive strength index (RSI), or scores from subjective questionnaires. For clinical assessments, binary or categorical outcomes (e.g., presence of effusion, unrestricted training) were recorded.
6) Comparison methods: Intra-subject comparisons (injured vs. uninjured limb), pre- vs. post-surgery measurements, or between-group comparisons when available.
7) RTS criteria: Thresholds used to define readiness for RTS, including functional, subjective, and clinical criteria.

Where quantitative outcome data were reported, values, units, and methods of calculation were recorded. Subjective and clinical outcomes were recorded as reported in each study, including any predefined criteria for RTS clearance. All extracted data were summarized to identify common assessment tools, outcome measures, and criteria used to determine RTS readiness across all studies.

C. Criteria effectiveness

Once the systematic review is performed, a smaller literature research will be conducted, aimed to address the effectiveness of the identified RTS tests. This will be conducted in a non-systematic manner, and will therefore not follow a predetermined query or PRISMA guidelines.

III. Results

A. Study Selection

The initial database search yielded a total of 505 records, with 224 from PubMed and 281 from Scopus. After removing 132 duplicates, 373 records remained for title and abstract screening. After the whole screening process fifteen studies were included in the final analysis. After this whole screening process, fifteen studies were included in the final analysis, representing approximately 6% of the initially identified records. Most articles were excluded because they reported only on RTS rates rather than focusing on assessment with quantitative measures or subjective questionnaires, or focused on assessing knee function after RTS. The study selection process is summarized in the PRISMA flow diagram in Figure 1.

B. Publication and study Characteristics

The characteristics of the included studies are summarized in Table 3. The studies were published between 2015 and 2025. Geographically, the majority of the studies were conducted in Australia (n=3) [26–28]. Two studies each were conducted in Qatar [29, 30] and the United Kingdom (UK) [10, 31]. The remaining studies were conducted in Austria [32], Canada [33], Japan [34], the Netherlands [35], Serbia [36], Hungary [13], the United States of America (USA) [37], and Spain [38].

Furthermore, the most common study design was case report (n=5) [10, 28, 31, 33, 34], followed by prospective cohort studies (n=4) [29, 35, 37, 38]. Other designs included cross-sectional studies (n=2) [26, 30], pilot studies (n=2) [13, 32], randomized controlled trial [36], and retrospective cohort study [27].

C. Athlete characteristics

Nine studies included both female and male participants [13, 26, 27, 32, 34–38], with only two

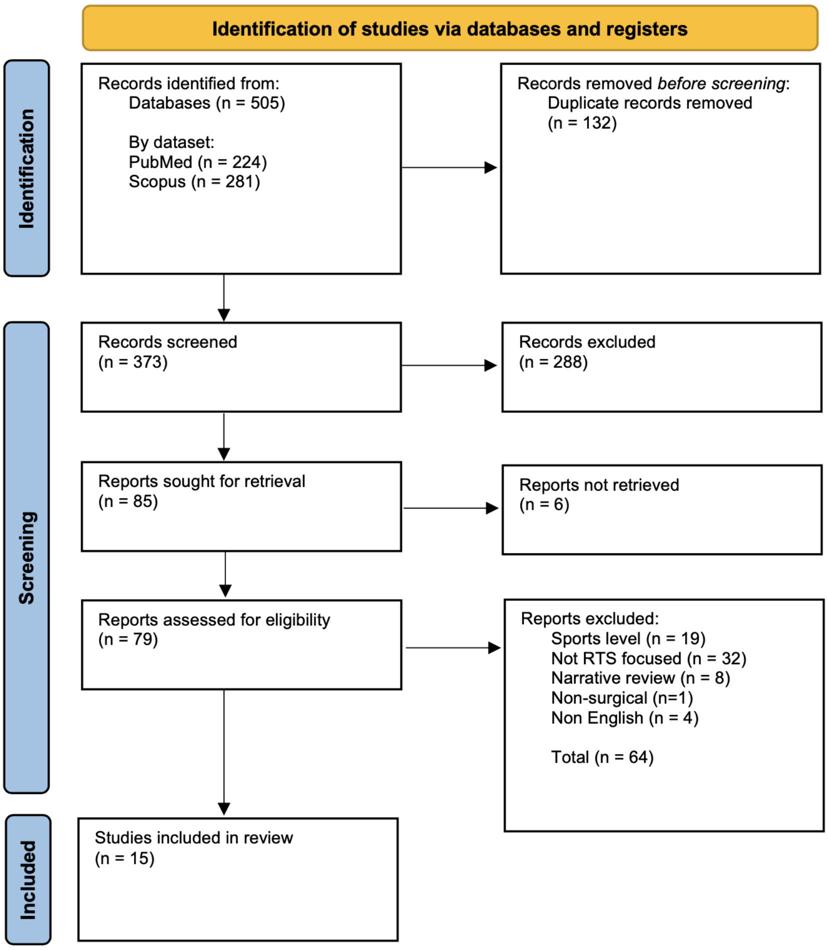

Figure 1. PRISMA flow diagram of the literature research [22].

reporting a higher number of female than male participants [34, 37]. Three studies included only male participants [10, 29, 30], and three studies included only female participants [28, 31, 33].

Three types of grafts were identified: hamstring tendon, bone–patellar tendon–bone (BPTB), and quadriceps tendon. When a combination of grafts was used, it always involved hamstring and BPTB (n=4) [29, 30, 32, 37], and in two studies the quadriceps tendon was also included [32, 37]. These were the only instances in which the quadriceps tendon was reported. Only once did BPTB account for the majority of grafts received in a single study [30]. Among studies that reported using a single type of graft, hamstring tendon was the most common (n=8) [10, 13, 26–28, 31, 33, 34], whereas BPTB was reported only twice [35, 36].

When looking at the sport types, soccer was the most frequently reported (n=9) [10, 13, 28–31, 35, 36, 38]. Followed by handball (n=4) [13, 29, 35, 36]. Five studies [26, 27, 32, 34, 37] have not reported what kind of sport the athletes were participating in.

As the reported sport level varied across studies, all included studies were categorized into three groups: competitive, elite, and professional. The *competitive* category includes studies reporting competitive athletes [13, 32], high-school or collegiate athletes [37], participants with a Tegner score of 6–7 [35], or train more than four days per week [26]. The *elite* category includes studies describing (semi-)elite athletes [28, 33], semi-professionals [38], or those with a Tegner score of 8 [27, 34]. The *professional* category includes studies that specifically reported professional athletes [29–31, 36–38]. This classification resulted in 4 studies categorized as competitive, 5 as elite, and 6 as professional, see Table 4.

Table 3. Publication and study characteristics of the included studies.

Author	Year	Location	Study design	Sport type	Sport level	Gender	Graft type	Reported RTS with criteria
E. Herbst et al. [32]	2015	Austria	Pilot	–	Recreational, competitive	Male (60.9%), Female (29.3%)	Hamstring (68.7%), Quadriceps (17.4%), BPTB (14.5%)	*Functional:* LSI ≥90% dominant, ≥80% non-dominant *Clinical:* Swelling, ROM, pain, clearance
P. Kyritsis et al. [29]	2016	Qatar	Prospective cohort	Soccer, handball, other	Professional	Male	Hamstring (70%), BPTB (30%)	*Functional:* LSI ≥90%; H/Q ratio deficit 10–15%
K.E. Webster et al. [26]	2018	Australia	Cross-sectional	–	1–3, & 4–7 days/week	Male (61.3%), Female (38.7%)	Hamstring	*Functional*: LSI ≥90% *Subjective:* IKDC ≥85, ACL-RSI ≥65 *Clinical*: knee effusion, unrestricted 4 weeks training
M.J. Jordan et al. [33]	2020	Canada	Case report	Alpine ski racing	Elite	Female	Hamstring	*Functional*: LSI ≥90%
M. Taberner et al. [31]	2020	UK	Case report	Soccer	Professional	Female	Hamstring	*Functional:* – *Subjective:* – *Clinical:* swelling, pain, clearance, muscle mass < 5%, unrestricted training
T. Kitaguchi et al. [34]	2020	Japan	Case report	–	Tegner: 8	Male (26.2%), Female (73.8%)	Hamstring	*Functional:* – *Clinical:* effusion, ROM
A. Klasan et al. [27]	2021	Australia	Retrospective cohort	–	Tegner: 8	Male (57.7%), Female (42.3%)	Hamstring	*Functional:* LSI ≥90% *Subjective:* – *Clinical:* effusion, ROM, Lachman unrestricted 8 weeks training
A.E. Ronden et al. [35]	2022	Netherlands	Prospective cohort	Soccer, handball, other	Tegner: 7±1	Male (75.7%), Female (24.3%)	BPTB	*Functional:* LSI ≥90% dominant, ≥80% non-dominant *Subjective:* IKDC ≥85, ACL-RSI ≥65
M.D.M. Stojanović et al. [36]	2023	Serbia	Randomized control trial	Soccer, handball, basketball	Professional	Male (63.6%), Female (36.4%)	BPTB	*Functional:* –
A. Mitchell et al. [10]	2023	UK	Case report	Soccer	Professional	Male	Hamstring	*Functional:* LSI ≥90% & compared to pre-injury levels
L. Maestroni et al. [30]	2023	Qatar	Cross-sectional	Soccer	Professional	Male	Hamstring (20%), BPTB (80%)	*Functional:* –
R.I.B. Syed et al. [13]	2024	Hungary	Pilot	Soccer, handball, rugby, gymnastics, tennis	Competitive	Male (50.0%), Female (50.0%)	Hamstring	*Functional:* – *Subjective:* –
N. Sharp et al. [28]	2024	Australia	Case report	Soccer	Semi-elite	Female	Hamstring	*Functional:* – *Subjective:* –
J.C. Brinkman et al. [37]	2025	USA	Prospective cohort	–	High school, collegiate, professional	Male (43.3%), Female (56.7%)	Hamstring, Quadriceps, BPTB	*Functional:* LSI ≥90% *Subjective:* ACL-RSI ≥65 *Clinical:* Lachman, Pivot-shift tests
V.L. Escamilla-Galindo et al. [38]	2025	Spain	Prospective cohort	Soccer	Semi- and professional	Male (76.6%), Female (23.4%)	–	Not reported

Abbreviations: ACL = anterior cruciate ligament; RTS = return-to-sport; RTC = return-to-competition; BPTB = bone–patellar tendon–bone; LSI = limb symmetry index; IKDC = International Knee Documentation Committee; ACL-RSI = ACL–Return to Sport Index; TSA = Total Score of Athleticism; ROM = range of motion.

D. RTS testing

In the reviewed studies several different test have been related to RTS assessment. The most relevant have been identified and will be elaborated on in this paragraph. A single study was not categorized, since it proposed a new RTS assessment criterion [38]. This study used skin temperature as the criterion and examined its relationship to the athletes' reported RTS time.

1. Functional test

Functional tests are used because they combine several skills and movements which mimic the demand of sport-specific tasks, such as acceleration,

Table 4. Each study categorized in their corresponding sport level.

Sport level	Study
Competitive	Herbst et al. [32], Syed et al. [13], Brinkman et al. [37], Ronden et al. [35], Webster et al. [26]
Elite	Sharp et al. [28], Jordan et al. [33], Escamilla-Galindo et al. [38], Klasan et al. [27], Kitaguchi et al. [34]
Professional	Kyritsis et al. [29], Taberener et al. [31], Stojanovic et al. [36], Maestroni et al. [30], Brinkman et al. [37], Excamilla-Galinod et al. [38]

deacceleration, landing, vertical and horizontal displacement, and changes of direction. Evaluating these tasks provides insight about the knee functions, specifically regarding the knee stability, lower limb strengths and proprioception [39, 40].

Several functional tests were reported in the reviewed studies as part of the RTS assessment. These have been categorized into four groups: hop tests, jump tests, strength test, and balance test. Figure 2 shows the frequency of the test used and Figure 3 summarizes these categories and their respective tests. None used all four of them.

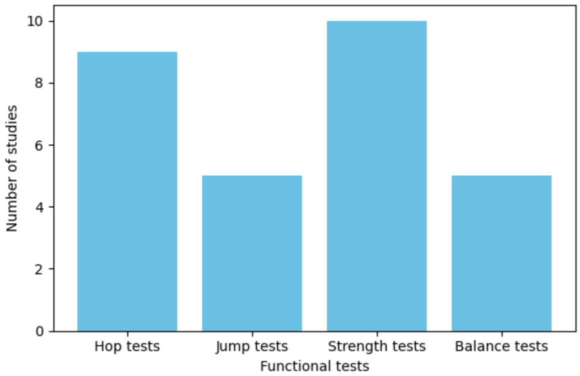

Figure 2. Frequency of functional test used.

Most included studies (n=14) used two or more functional test categories. With only one study [31] reported to have used only one jump test. Nine studies [13, 26, 29, 30, 32, 34, 35, 37] have chosen to incorporate two categories in their test battery. The most frequently (n=5) [26, 27, 29, 34, 37] reported combination of functional tests used is the hop tests combined with strength tests. Most studies using three functional tests opted to add jump tests to it (n=2) [10, 36]. This all is summarized in Table **??** in Appendix 3.

2. Hop test

Hop test require the athlete to accelerate (take off) and de-accelerate (land) on the same leg. This test is mainly used to assess the athlete's ability to produce horizontal power and maintain neuromuscular control during landing [41].

Eight studies reported to have used hop test [10, 26–29, 34, 36, 37], all of which used single-leg (SL). The most commonly used is the SL for distance (n=6) [27, 28, 34, 36] and the SL triple (n=5) [27–29, 36, 37]. Other tests are the SL cross-over (n=3) [26, 28, 29] and 6m hop for distance [28].

In the SL for distance test, the participant is asked to stand on one leg, jump as far as possible, and land on the same leg again. During the tasks the arms are free to move for balance control. If a secondary (smaller) hop is needed to maintain balance or if the participant falls, the trial is considered invalid.

Similarly, the SL triple hop involves three consecutive SL hops on the same leg. While the SL cross-over hop also consists of three consecutive hops and requires the participant to jump over a midline after each hop.

Each hop test is repeated multiple times, with the furthest results being noted. With the maximum distance the limb symmetry index (LSI) is calculated. The LSI is calculated by:

$$LSI = \frac{injured\ leg\ score}{uninjured\ leg\ score} * 100\% \qquad (1)$$

The 6 meter hop for time is an exception to this, here the time is recorded for the athlete to cover the 6m. This test was reported to be used once [28]. The participant performs large SL hops immediately following each other for a distance of 6 meter. The time it takes will noted and used for assessment.

3. Jump test

While jump tests and hop tests share similarities in what they assess [39], the main difference is that jump tests primarily evaluate vertical power. By incorporating tasks that minimize ground contact time, jump tests also assess the efficiency of the stretch-shortening cycle [42].

A total of eight studies [10, 27, 30–33, 35, 36] have reported to use jump tests, where all of them used SL and/or double legged (DL) counter movement jumps (CMJ).

For a DL-CMJ the participant is instructed to stand fully upright, with their feet pointing forward. They were than asked to descent as low as possible. As soon as they reached their lowest point, they reversed the movement and jumped as high as possible. The landing was again on both feet. During the duration of the tasks the hands remained on the hips. During the airborne phase, the knees were kept extended, which is important for accurately calculating jump height. For the SL-CMJ the same protocol was used, except for the fact that one knee had to be bent at 90 ° during the test and arms were free to move for balance control.

The SL-drop jump (DJ) is a test that was performed by one study [10]. During this test, the participant is asked to drop from a 15 cm height

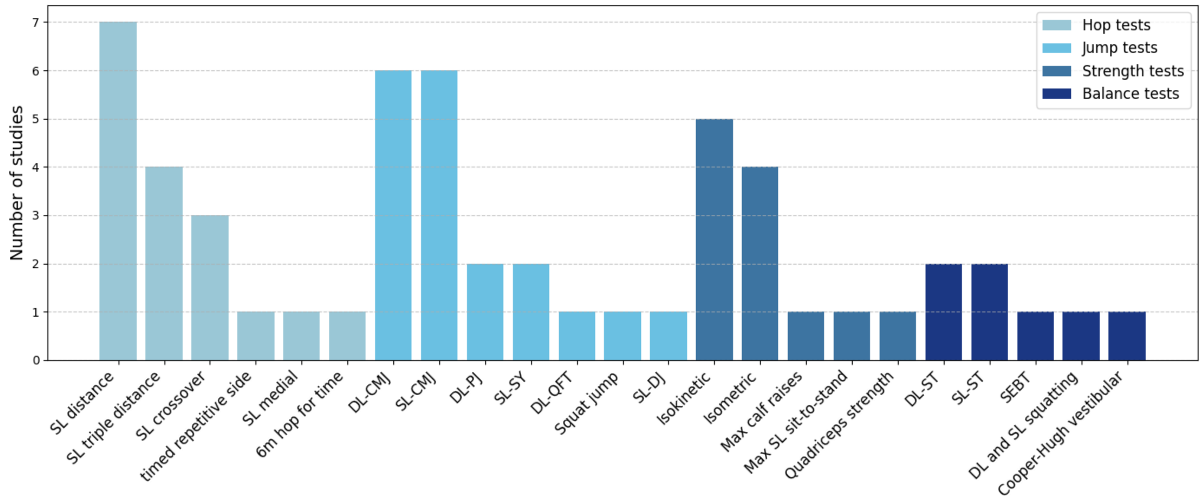

Figure 3. Frequency of individual functional test grouped by category.
CMJ = Countermovement Jump, DJ = Drop jump, DL = Double-legged, PJ = Plyometric jump, QFT = Quick feet test, SEBT = Star Excursion Balance Test, SL = single legged, ST = Stability test, SY = Speedy jump

step. When hitting the ground, he performs an all out vertical jump while spending as little time as possible on the ground. This evaluates the stretch-shortening cycle of the muscles. Upon landing the again the participant must stay balanced. Throughout the entire tasks participant's hands were placed on the hips, and the task was performed on one leg. The knee remained fully extended during the jump.

From each jump test the flight time (t_{flight}), and contact time ($t_{contact}$) for the SL-DJ, was obtained. Using the t_{flight} and knowing the gravitational force (g), the vertical jump height (h_{jump}) was estimated:

$$h_{jump}[m] = \frac{g[m/s^2] * t_{flight}^2[s]}{8} \quad (2)$$

For the SL-DJ, the h_{jump} was combined with the $t_{contact}$ to calculate the reactive strength index (RSI) Equation 3. The RSI provides a measure of the athlete's ability to rapidly produce force during the stretch-shortening cycle of the leg muscles. Mechanically, the jump height reflects the potential energy gained, which corresponds to the external work performed, while dividing by contact time yields an estimate of average power normalized to contact duration. This makes the RSI a metric for assessing lower-limb reactive performance.

$$RSI = \frac{h_{jump}[m]}{t_{contact}[s]} \quad (3)$$

With the jump height and/or RSI the LSI was calculated again using Equation 1.

To obtain the t_{flight} and $t_{contact}$, studies used a contact mat [36], accelerometers (n=2) [32, 37], or force plates (n=5) [10, 30, 31, 33], the latter allowing determination of rate of force development (RFD) from force input.

4. Strength test

Strength tests are used to quantify both isokinetic and isometric strength of the quadriceps, hamstrings, and other lower-limb muscles that directly influence knee function and stability. These tests provide objective measures of muscle capacity, and help identify deficits that may compromise joint stability [43].

A total of nine studies have reported to evaluate the quadriceps and/or hamstring using strength tests. Most of them either chose to measure isokinetic (n=4) [26, 29, 30, 34] or isometric strength (n=3) [13, 33, 36] only. One study [10] chose to use both isokinetic and isometric tests.

The isokinetic strength is measured at 60, 180, and 300 °/s using a dynamometer. Two studies [10, 33] reported to have used a dynamometer to measure the isometric strength. One study [13] used a force frame to measure the isometric strength, while the other opted to use a flywheel [36]. For the isokinetic test the main outcome measures were the peak torque and quadriceps-hamstring (Q/H) ratio. While for the isometric the RFD was reported to be used. The peak torque and the peak RFD are used to calculate the LSI. The Q/H ratio was used to determine the muscle deficit, it has not been reported how this was converted.

Noticeable was that only one study [28] used the soleus and gastrocnemius muscles in their strength analysis as well.

5. Balance test

The last group of functional assessments identified consists of balance tests. They are used to identify impaired postural control and altered proprioceptive strategies [44].

Five studies [13, 27, 28, 32, 35] reported to have used them. Two of them [32, 35] used the DL and SL stability test (ST). To perform the DL- and SL-ST the participant is asked to balance on a balance disk for 20-30 seconds. The software also calculated the stability index based on the position. The stability index of each leg was again used to obtain the LSI.

Other test used are the Star Excursion Balance Test (SEBT) [27], the Cooper-Hugh vestibular test [28], and (bi- and unilateral) squats [13]. The latter was performed on force plates to obtain the center of pressure (CoP).

6. Additional functional test

Besides the four identified functional tests, three studies [10, 29, 31] have also incorporated field specific training into the test battery. Some (n=2) [10, 31] have reported to use GPS data to monitor the training load during the whole process.

A smaller group of studies (n=2) [26, 27] have embedded the anterior-posterior laxity into the RTS assessment as well. The knee laxity was objectively assessed by measuring the anterior translation of the tibia with respect to the femur using a KT-1000 arthrometer. A comparison between the involved and uninvolved limbs was made by subtracting the average anterior displacement of the uninvolved leg from that of the involved leg.

Additionally, the running t-test was performed in one study [29]. This test examens the agility during running with implemented change of directions. Participants ran forward 10 meter, followed by 5 meter of side-steps to the right, 10 meter of side-steps to the left, 5 meter of side-steps to the right, and finishing with a 10 meter backward run back to the starting position. The time taken to complete the run is recorded and compared to the other limb. This test is mainly used to track progress during the duration rehabilitation.

7. Subjective data

As addition to these functional test, subjective data was gathered as well. Four subjective tests were found to be used in RTS assessment: International Knee Documentation Committee (IKDC) [45], Anterior Cruciate Ligament - Return to Sport Index (ACL-RSI) [46], Lysholm [47], and Knee Osteoarthritis Outcome Score (KOOS) [48]. All of these subjective test are in a questionnaire format with 100 as maximum score.

The IKDC evaluates symptoms, function, and sports activity, including questions on pain, stiffness, swelling, and the ability to perform daily and sport-specific tasks. The ACL-RSI focuses on psychological readiness for return to sport, assessing confidence, emotions, and risk appraisal related to reinjury. The Lysholm score primarily assesses knee symptoms such as instability, locking, pain, and swelling during functional activities. The KOOS expands on the assessment of knee-related symptoms and function by including domains related to sport and recreation as well as knee-related quality of life.

One of the primary subjective test reported is the IKDC (n=6) [13, 26–28, 35, 37]. The questionnaire assess symptoms, functional limitations and sport activity levels of the athlete. The responses are transformed into a quantified score, providing a measure of the athlete's knee health and overall function.

ACL-RSI was reported the same amount of times as IKDC (n=6) [13, 26–28, 35, 37]. ACL-RSI, unlike the afore mentioned tests, focuses on the athlete's emotions, confidence and perception of risk related to RTS specifically. A higher score correlates with a higher psychological readiness.

Less frequently mentioned is the Lysholm test (n=2) [27, 37]. This test highlights eight domains: pain, instability, locking, swelling, limp, support, stair climbing, and squatting. With as primary goal to estimate the knee's instability. Higher scores reflects better knee stability and function.

The least reported test is the KOOS [35]. Unlike the Lysholm test, the KOOS covers five domains: pain, symptoms, (sport) activity, and knee-related quality of life. This makes it an effective tool in assessing short- and long-term outcomes after knee injuries. Better knee function is reflected by higher scores.

All of the time when IKDC was reported ACL-RSI was used, and vice versa. KOOS and Lysholm were used as comparison method in the prospective studies and did not contribute to the RTS assessment directly.

One study stated that psychological readiness was used, but did not objectively measure this [33].

For the KOOS questionnaire, no clear threshold values was reported [35].

Several other studies (n=3) [13, 27, 28, 37] reported the use of subjective measures without stating explicit criteria for RTS clearance.

E. RTS criteria

To finalize the RTS assessment, the outcome measures are compared to predefined criteria. The following sections summarize the quantified and subjective criteria reported for each type of test (functional, subjective, and clinical).

A few studies (n=5) [13, 28, 30, 36, 38], have not reported criteria for any of the used tests. The test were used for comparison in the study itself. In these studies, the tests were applied for comparative purposes within the study population.

1. Functional test criteria

Generally, studies using LSI set the passing criterion at ≥ 90% (n=5) [10, 26, 27, 29, 33, 37]. Two studies [32, 35] distinguished between the dominant and non-dominant leg when setting the criteria values, applying ≥ 90% if the operated leg was dominant and ≥ 80% if it was non-dominant.

A few instances were found where LSI was not used. An example is at the strength test, where the H/Q ratio was transformed the muscle deficit. For the muscle deficit a criteria of 10%-15% was reported to be used [29].

Instead of the intra-subject comparison metric LSI, some studies have evaluated RTS using the Total Score of Athleticism (TSA) [30] or pre-injury levels [10]. The TSA is a value that allows for comparison across similar athletes with comparable training demands and constraints.

2. Subjective criteria

Among studies reporting subjective outcome measures, only a limited number defined specific quantitative criteria for RTS clearance. An IKDC score of ≥ 85 was reported to be sufficient to be cleared for RTS (n=2) [26, 35], while for the ACL-RSI a score of ≥ 65 was applied as the clearance criteria (n=3) [26, 35, 37].

The Lysholm score was used in two ways: to compare outcomes between different graft types [37], and to compare athletes who returned to sport with those who did not [27], but no specific criteria were defined.

3. Clinical criteria

Additionally to the functional and subjective criteria, some studies have reported to use clinical clearance as well. For the clinical clearance most frequently looked at was the knee effusion (n=3) [26, 27, 34] or swelling (n=2) [31, 32]. Furthermore, full or symmetrical range of motion (ROM) (n=3) [27, 32, 34] and pain (n=2) [31, 32] were reported.

Some studies incorporated clearance from a physiotherapist [32] or surgeon [31] prior to RTS assessment.

Knee stability was assessed either using the Lachman test (n=2) [27, 37] or the Pivot-shift test [37], while a study [34] did not define a specific stability test. Muscle mass asymmetry of < 5% was used as a criterion in one study [31].

Finally, unrestricted training was included as a clinical criterion in some studies. Most of them used 4 [26] or 8 weeks [27] of training as passing criteria. While one had a subjective measure specified as: “sufficient on-field training sessions" [31].

F. Criteria evaluation

After identifying the tests and criteria used to determine RTS readiness, the question remains: how effective are these measures in preventing re-injury? Evidence suggests that athletes who pass all RTS criteria have a lower re-injury rate (16%) compared with those who do not pass the criteria (26%) [49]. In the following section, the effectiveness of the identified assessments will be examined both individually and in combination. However, a recent review by Figueroa et al. highlighted that the reasons why athletes fail to RTS is barely described in the existing literature [50].

As this review has shown, functional test are widely adopted. Van Melick et al. has reported that the usage of hop tests, specifically the SL for distance test, is significantly associated with a reduced ACL re-injury [51]. In their prospective observational cohort study, 7 of 62 athletes who did not pass the RTS criteria sustained a second ACL injury, whereas no re-injuries were reported among the 35 athletes who passed the RTS assessment. However, they have not found a significant relevance to relate strength test for ACL re-injury. Similarly, it was demonstrated by Nawashreh et al. that the 6-m timed hop test integrated in a comprehensive test battery, is associated with lower re-injury rates as well [52].

A mixture of jump test are widely used in the RTS assessment, with CMJ as the most dominant identified in this review. In literature it has been found that the SL-CMJ can reduced the re-injury risk from 10% to 4% when meeting the ≥ 90% LSI criteria [51]. This finding is supported by a systematic review demonstrating that the majority of their included study using SL-CMJ, associated it with lower risk of knee injury [53]. In contrast, the same review reported that evidence linking DL-CMJ performance to reduced knee injury risk is limited and less consistent [53]. Interestingly, although less frequently reported in the present review, DJ performance has also been associated with a reduced risk of lower extremity injury [53].

Furthermore, the study by Kyritsis et al. investigated the likelihood of reinjury based on whether specific discharge criteria were met in a large sample (n=158) [29]. Their findings demonstrated that a low H/Q strength at $60°/s$ ratio was associated with an increased risk of ACL graft rupture. Importantly, this imbalance primarily reflected insufficient quadriceps strength rather than excessive hamstring strength.

However, although similar conclusions have been proposed by others [14, 54, 55], direct evidence supporting this relationship remains limited. This does not mean that the strength test is ineffective. On the contrary, as Kyritsis et al. shows, athletes passing their test battery, which includes both hop and strength test, reduces graft rupture by four times [29]. Specifically, 12 of 116 fully discharged athletes sustained a graft rupture, compared with 14 of 42 athletes who were not fully discharged. These findings suggest that multi-functional test assessment is an effective measure in reducing re-injury.

The balance test, especially the SEBT, shows great intra-tester reliability and detection of dynamic balance deficits [56]. However, more research is needed to determine which balance test can accurately predict RTS [57].

Psychological test are currently widely used in test batteries. Regression analyses by Faleide et al. has identified both the ACL-RSI and IKDC as significant predictors of successful return to pre-injury performance, with the ACL-RSI showing a sensitivity (57%–97%) and specificity (63%–84%) [58]. Further studies have also found a relation between ACL-RSI and successful RTS passing rates [59, 60]. A qualitative study by Betsch et al. even showed that physicians considered this as an important factor [17].Although it could be hypothesized that psychological readiness is linked to proprioceptive ability, no evidence has been found to support this association. Instead, psychological readiness is more strongly related to fear of reinjury [34, 50]. These findings highlight the importance of integrating psychological assessment into RTS decision-making.

It has been found that, studies combining functional and psychological criteria show more promising outcomes [14, 49, 58]. As stated before, from all athletes meeting all RTS criteria sustain approximately 16% a re-injury versus 26% when not meeting the criteria [49]. Another article reports, 6% versus 38% [14]. These examples show the effectiveness of using multi-model assessment. When looking at the reviewed articles, many used both psychological and functional assessment and thus, already incorporate the multi-modal assessment.

Rehabilitation protocols relying solely on time from reconstruction to RTS, are less frequently used but are still used. Time is often considered important because it is associated with recovery and lowering re-injury risk. Most rehabilitation process, use a combined time-criteria-based approach [17]. This is important, because when a criteria-based approach is used without considering (healing) time, athletes risk to RTS too early. Which is associated with a 70% higher risk of re-injury [29]. Furthermore, studies that investigated the RTS rate 6 months post-ACLR, reported to see lower passing rates compared to assessment at 9 or 12 months [14, 58–60]. Grindem et al. concluded that with every month (up to 9 months) that RTS was delayed, the reinjury risk was reduced by 51%. This indicates that delaying the assessment to nine months greatly reduces re-injury risk, emphasizing that time after reconstruction is an effective measure in RTS decision making.

All discussed highlight the effectiveness of the test batteries with regards to reducing the re-injury risk, especially when combining different types of assessment measures. Single-leg hop and CMJ tests, quadriceps strength, and psychological readiness are particularly predictive, while multi-modal assessments outperform individual tests. Additionally, delaying RTS assessments up to nine months post-surgery further lowers reinjury risk, highlighting the importance of a comprehensive, timed, and individualized approach.

IV. Discussion

This study summarizes current literature on kinematic and kinetic measures used for RTS assessment following ACLR. The analysis of fifteen studies revealed that a heterogeneous set of assessment tools, and criteria is used, underscoring the lack of standardization. Moreover, while these tests reflect functional performance, they do not directly capture the mechanical behavior of the knee's ligaments, muscles, or other supporting structures.

A. Functional Assessments

A broad range of functional tests was identified, grouped into four main categories: hop, jump, strength, and balance tests. All reviewed studies have used at least two of these categories, which is as recommended [61].

Hop tests, particularly the SL hop for distance and SL triple hop, were most frequently used. This aligns with previous research that considers hop tests reliable and sensitive indicators of lower-limb symmetry and functional recovery [51, 52]. However, as previously mentioned, this alone is insufficient to accurately clear someone for RTS. Additionally, the load absorption performed in these test, occurs across the entire lower-limb kinetic chain (hip, knee, and ankle), rather than being isolated from the knee alone [62]. As a result, these tests reflect the lower-limb function rather than providing a direct evaluation of knee structures, such as the ACL.

Jump tests, especially CMJ, were widely adopted in the included articles, with many studies quantifying jump height, RFD, or RSI. These metrics provide insight into load absorption and force generation of the muscles strategies, specifically the stretch-shortening cycle, that cannot be derived solely from hop tests [63]. Just like with hop test, the load absorption and muscle force generation is across the whole lower-limb kinetic chain [64], making a direct knee evaluation in this form hard.

Additionally, the use of different measuring equipment (force plates, contact mats, and accelerometers) during these tests, complicates comparisons between the studies. Since accelerometers have shown poor reliability, force plates remain the golden standard [65]. Although the CMJ metrics show an meaningful integration of the lower-limb kinetic data, the various different measuring tools identified complicates the establishment of standardized thresholds.

Strength testing was also frequently included, with both isokinetic and isometric test used to assess the quadriceps and hamstring ratio. Despite isokinetic testing being the preferred method by the reviewed studies, some studies have incorporated isometric assessments using dynamometers. Dynamometers were used due to their reliability, standardized protocols, and validity [66]. Interestingly, Sharp et al. was the only one incorporating the calf muscles (gastrocnemius and soleus) in their strength analysis [28]. Recent literature indicates that neglecting the contribution of the calf muscles may overlook important factors in ACL injury prevention and rehabilitation [67]. This is because the calf muscles can generate posterior shear force on the tibia, helping to counteract the anterior shear to which the ACL is prone [68]. Strangely, most studies focused on the Q/H ratio, probably due to their proven direct role in the knee movement [69].

Balance evaluations were the least mentioned, though those using the CoP-based measures provided valuable insights into postural control [27, 32, 35]. They appear promising with great reliability [56], but the exact predictability with regards to RTS is unknown [57]. Which could also be seen as the reason why most studies did not chose to incorporate it. However, observing whether an athlete leans toward the injured or non-injured leg can offer insights into load bearing and compensatory mechanisms. Future research should explore the relationship between such balance metrics and RTS outcomes.

B. Subjective and Clinical Assessments

Subjective outcome measures, such as the IKDC and ACL-RSI, complement functional tests by providing insight into factors that objective measures cannot capture. While the IKDC reflects knee function, the ACL-RSI assesses psychological readiness, which has been shown to influence RTS outcomes [59, 60]. This distinction highlights that successful RTS depends not only on physical recovery but also on the athlete's confidence, motivation, and fear of re-injury. In contrast, measures like KOOS and Lysholm primarily track short- and long-term recovery rather than readiness for sport-specific performance, limiting their direct utility in RTS decision-making. Integrating both physical and psychological assessments allows clinicians to better identify athletes who are truly prepared to return to play and may help reduce the risk of re-injury.

The widespread use of psychological assessments demonstrates that the psychological state of athletes is increasingly recognized as a key component of RTS decision-making. Importantly, several studies report that athletes may meet objective physical recovery benchmarks yet still fail to return to sport or experience delayed RTS when psychological readiness is low [26, 29]. This suggests that psychological factors act independently of physical capacity and can limit the translation of physical recovery into successful RTS.

Non-knee–related determinants, particularly fear of re-injury, reduced confidence in knee function, and anxiety during sport-specific tasks, are frequently identified as primary barriers to RTS [34, 50]. Psychological readiness consists of confidence in the injured knee, realistic expectations regarding performance, and motivation to resume sport participation [70]. Deficits in any of these domains may therefore increase the risk of not being able to RTS, despite adequate physical function.

The commonly used questionnaires, such as the ACL-RSI, attempt to capture these dimensions by quantifying emotional responses, confidence, and risk appraisal related to RTS. Their widespread adoption reflects the growing recognition that psychological readiness is independent of physical recovery and should be addressed alongside physical rehabilitation.

Reviewed studies also included clinical criteria before RTS assessment could be performed. Criteria such as pain, effusion, and ROM, were the dominant ones with some also using expert clearance. Additionally, sport-specific trainings were rarely reported and only utilized for professional athletes [10, 31]. However, the criteria was often descriptive rather than quantitative, making it hard to evaluate.

C. RTS Criteria

Most studies employed the LSI as the main decision metric, where the cut-off value of ≥ 90% was most common. Though some studies accounted for leg dominance by adjusting the threshold to 80–90%. A well known and documented problem of the LSI-criteria is the overestimating of functional performance [29, 35, 71]. Other studies have reported to substitute this for a body height ratio [72] or biomechanical values such as joint angles compared to healthy subjects [73]. However, the preferred comparison method uses pre-injury values, or match it to healthy controls for a more accurate assessment [71]. Only one study has reported to use this, and the pre-injury values were used to normalize the LSI [10].

It became evident that both objective, subjective, and clinical components are used in the RTS criteria. However, most studies do not clearly define how these components are weighted in the final RTS decision. Although both physical and psychological readiness are widely recognized as essential for successful RTS [17], these components are often treated as separate and parallel outcomes rather than being linked through underlying knee function.

This is surprising given that the ACL acts not only as a mechanical stabilizer of the knee, but also as a sensory structure involved in proprioception and neuromuscular control. Changes in sensory input after ACLR may affect movement confidence, perceived knee stability, and fear of re-injury, thereby influencing psychological readiness. However, most reviewed studies do not examine this interaction, leaving RTS frameworks largely detached from the ACL's combined mechanical and sensory function.

D. Alternative RTS Indicators

The ongoing process of introducing innovative approaches towards RTS assessment is reflected by the study of Escamilla-Galindo et al, where they have looked at skin temperature around the knee for assessment. Specifically, asymmetrical skin temperature patterns around the knee were detected, indicating asymmetries in local inflammation, blood flow, and metabolic activity [38]. Since this study was relatively new (2025), implementation into existing batteries has not been seen yet.

The use of GPS to monitor training load reflects an effort to link lab-based assessments with real-world performance. GPS can estimate the training load, by tracking movement volume, intensity, and distance of on-field training. This provides insight into overall fitness and workload progression, but it does not directly measure knee mechanics, ligament loading, or neuromuscular control of the ACL. While it can help athletes gradually increase activity and lower the risk of general injuries, it cannot replace tests that assess the knee function more directly.

As highlighted in this review, most functional tests assess the lower-limb kinetic chain as a whole, which includes the knee but does not isolate its contribution. More detailed biomechanical analyses, such as inverse dynamics, can separate the roles of the hip, knee, and ankle [73, 74]. However, these approaches are not yet widely adopted in clinical practice. Even with inverse dynamics, the direct mechanical behavior of the ACL and other knee structures cannot be measured. As these technologies become more accessible, they could be used for advanced analyses, such as estimating ACL load, providing a more direct assessment of knee readiness.

E. Future Research

The diversity of RTS test and criteria across the reviewed studies, emphasizes that there is no standardized test battery and that the effectiveness of the functional tests are not well investigated. The latter one is complicated due to the non-standardized batteries. However, longitudinal studies have been able to overcome this hurdle, and highlighted the effectiveness of some test. These valuable research should be continued.

Additionally, future research should focus on expanding the use of advanced biomechanical analyses to achieve a more precise evaluation of knee function and the contribution of individual joint structures. While functional tests assess the lower-limb kinetic chain as a whole, tools such as inverse dynamics become more accessible, which can help isolate for joint contribution. Although these methods are not yet widely used in clinical practice, it can be argued that they have the potential to estimate ACL load and more directly assess knee readiness, providing objective data that could improve RTS decision-making.

Furthermore, future research should aim to establish normative data and criteria accounting for sport type, sex and sports level. Creating a normative dataset would allow for more precise assessment.

F. Limitations of Current Evidence

The reviewed studies showed great differences in design, and measurement tools. Many relied on small sample sizes or single-case designs, making comparisons difficult.

Additionally, no time-based rehabilitation protocols were included while this was expected. A quantitative study by Betsch et al. showed that some physicians rely fully on a time-based approach in RTS decisions [17]. This study therefore gives a misrepresentation of all the used assessments.

V. Conclusion

RTS assessment is a non-standardized, multimodal approach, where functional and psychological test are important factors found in literature. Functional test can be distinguished in hop, jump, strength, and balance test. At least two different test are used and complemented with psychological tests (ACL-RSI and IKDC) to make an informed decision.

The effectiveness of these test is barely investigated, but several tests such as the SL hop for distance, CMJ, and isokinetic strength test at $60°/s$ have shown to be effective in reducing re-injury risks. Combining functional and psychological criteria appear most effective in minimizing re-injury. Although time-based approaches were not specifically mentioned in the reviewed articles, this is still taken into account during the RTS decision-making. Combining all three elements decreases the chance of re-injury the most, and is thus most effective.

Most functional tests, however, only indirectly assess ACL function. Future RTS protocols should aim to standardize the inclusion of at least one functional, one psychological, and one temporal criterion, and efforts should be made to incorporate direct measurements of knee function, such as ACL load estimation through biomechanical modeling or imaging, to further improve RTS assessment and athlete safety.

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Appendix 1 - Abbreviations

ACL	*Anterior cruciate ligament*
ACL-RSI	*Anterior cruciate ligament – return to sport after injury*
ACLR	*Anterior cruciate ligament reconstruction*
AR	*Auto reviewer*
BPTB	*Bone–patellar tendon–bone*
CMJ	*Countermovement jump*
COP	*Center of pressure*
DJ	*Drop jump*
DL	*Double leg*
IKDC	*International knee documentation committee*
KOOS	*Knee injury and osteoarthritis outcome score*
LSI	*Limb symmetry index*
PICOS	*Population, intervention, comparison, outcomes, study design*
PRISMA	*Preferred reporting items for systematic reviews and meta-analyses*
Q/H	*Quadriceps to hamstring ratio*
RFD	*Rate of force development*
ROM	*Range of motion*
RSI	*Reactive strength index*
RTS	*Return to sport*
SEBT	*Star excursion balance test*
SL	*Single leg*
TSA	*Total score of athlicism*

Appendix 2 - Full queries

MEDLINE-PubMed
("return to sport"[Mesh] OR ("readiness" AND "sport") OR "RTS" OR "RTP")
AND
("anterior cruciate ligament"[Mesh] OR "ACL")
AND
("professional" OR "elite" OR "high performance" OR "competitive" OR "high-level" OR "semi-professional")

Scopus
TITLE-ABS-KEY (((return OR readiness) W/2 sport OR (return OR readiness) W/2 play OR "RTS" OR "RTP"))
AND
TITLE-ABS-KEY (("anterior cruciate ligament" OR ACL))
AND
TITLE-ABS-KEY (("professional" OR "elite" OR "high performance" OR "competitive" OR "high-level" OR "semi-professional"))

Appendix 3 - Identified functional performance per study

Table 5. Functional tests identified per study and category.

Study	Hop tests	Jump tests	Strength tests	Balance tests
Herbst et al. [32]	–	DL-CMJ, SL-CMJ, DL-PJ, SL-SY, DL-QFT	–	DL-ST, SL-ST
Kyritsis et al. [29]	SL distance, SL triple distance, SL crossover	–	Isokinetic strength	–
Webster et al. [26]	SL distance, SL crossover	–	Isokinetic quadriceps strength	–
Jordan et al. [33]	–	DL-CMJ, Squat jump	Isometric leg press, isometric knee extension/flexion	–
Taberner et al. [31]	–	DL-CMJ	–	–
Kitaguchi et al. [34]	SL distance	–	Isokinetic strength	–
Klasan et al. [27]	SL distance, timed repetitive side hop	SL-CMJ	–	SEBT
Ronden et al. [35]	–	DL-CMJ, SL-CMJ	–	DL-ST, SL-ST
Stojanovic et al. [36]	SL distance	SL-CMJ, SL-DJ	Isometric leg strength	–
Mitchell et al. [10]	SL triple distance, SL medial hop	DL-CMJ, SL-CMJ	Isokinetic quadriceps, isometric hamstring strength	–
Maestroni et al. [30]	–	–	Isokinetic hamstring /quadriceps strength	–
Syed et al. [13]	–	–	Isometric hamstring /quadriceps strength	DL and SL squatting
Sharp et al. [28]	SL distance, SL triple distance, SL crossover, 6 m hop for time	–	Max calf raises, max SL sit-to-stand	Cooper–Hugh vestibular test
Brinkman et al. [37]	SL triple distance	–	Quadriceps strength	–

Abbreviations: CMJ = Countermovement jump; DJ = Drop jump; DL = Double-legged; PJ = Plyometric jump; QFT = Quick feet test; SEBT = Star Excursion Balance Test; SL = Single-legged; ST = Stability test; SY = Speedy jump.

B

Marker error

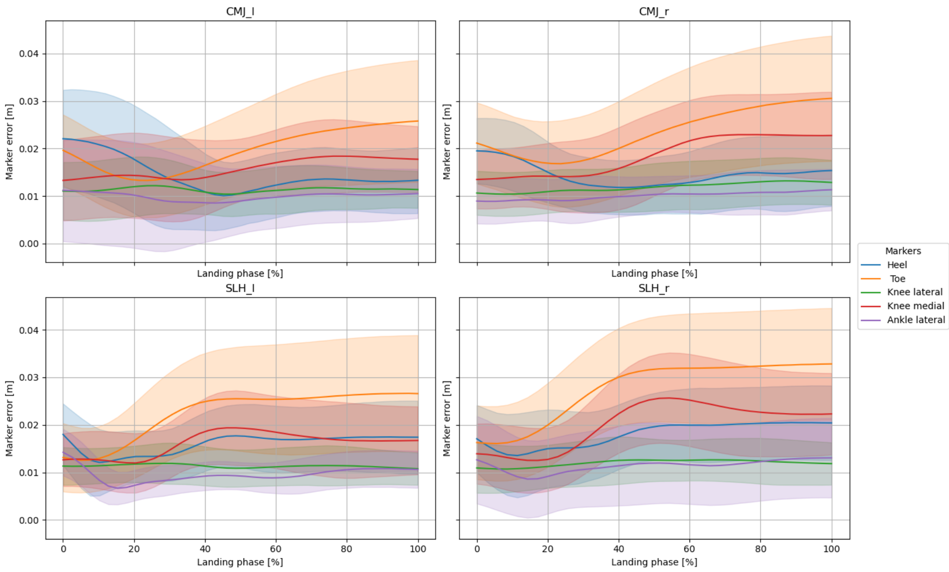

Figure B.1: The mean marker error (lines) and the standard deviation (opacity area) of important leg markers during the landing phase per functional tasks (SLH and uCMJ) and leg (l = left, r = right).

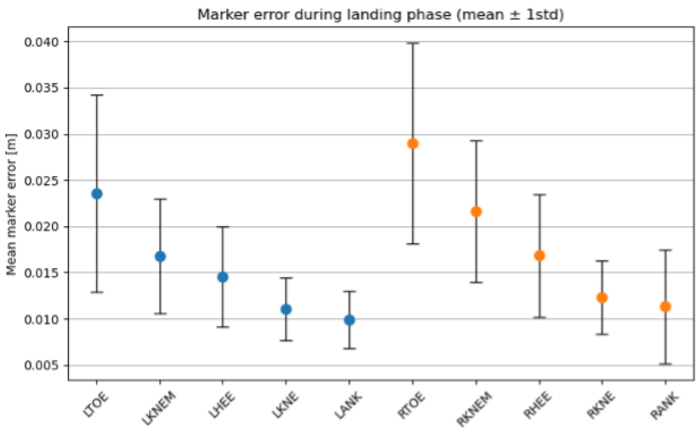

Figure B.2: Mean error (dots) and standard deviation (lines) of the important leg markers left (blue) and right (leg) averaged over all included trials.

C
Force contribution

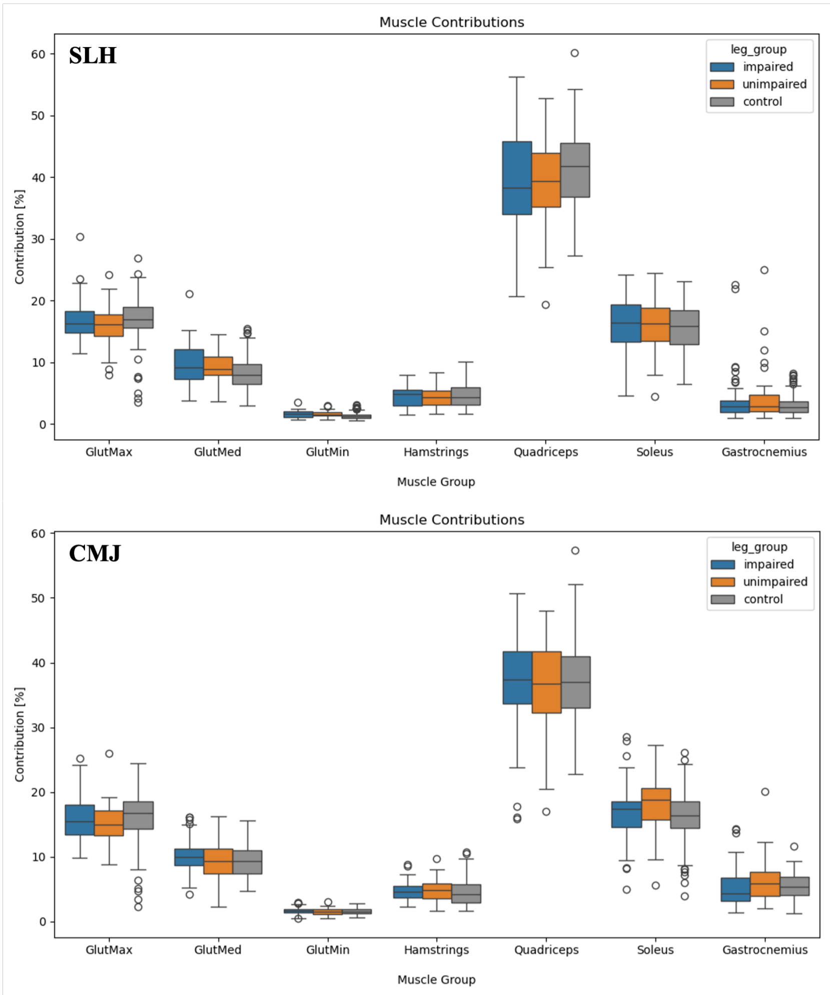

Figure C.1: Force contribution of leg muscle groups of the SLH (top) and uCMJ (bottom) tasks devided by impaired, unimpaired, and control group.

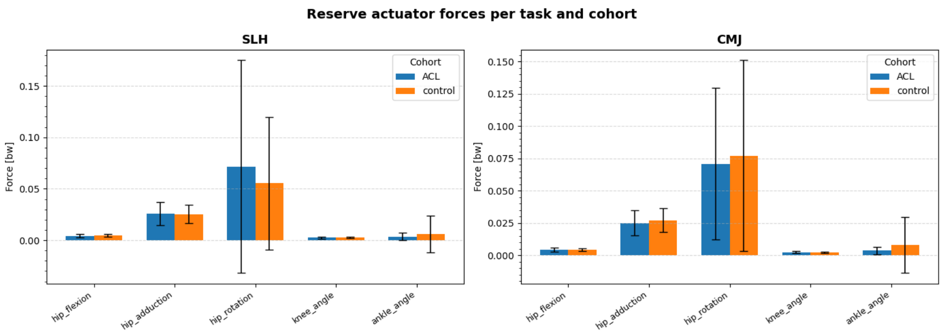

Figure C.2: The average forces produced during the SLH (left) and uCMJ (right) compared between the ACL and control group (see Table 2.1).