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Return-to-sport assessment for preventing ACL re-injury: An experimental and musculoskeletal modeling approach

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Return-to-sport assessment for preventing ACL re-injury: An experimental and musculoskeletal modeling approach

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Abstract

This study aimed to propose a return-to-sport procedure for preventing a second anterior cruciate ligament (ACL) injury in football (soccer) players. Six professional male football players, three of whom had undergone ACL reconstruction (ACLR), performed normal overground walking gait tests. Muscle activations and forces, knee joint kinematic and kinetic parameters, and ACL loading were obtained using electromyography (EMG) and OpenSim musculoskeletal analysis. Asymmetry in muscle activation between the dominant and non-dominant legs was observed in both the ACLR and control groups and was more pronounced in the ACLR subjects. Significant limb asymmetries were also observed in the gait cycle of the ACLR subjects. These asymmetries after ACLR were associated with increased ACL loading and, consequently, a higher risk of ACL re-injury. Therefore, an injury risk index (IRI) was introduced to assess the risk of a second ACL injury based on the maximum ACL graft force during the gait cycle. The IRI was significantly higher in the ACLR group than in the control group. Based on these findings and the proposed index, a return-to-sport procedure was developed that accounts for ACL loading in both the injured and contralateral legs. This procedure may help physicians prescribe specific rehabilitation programs for football players after ACLR and reduce the risk of ACL re-injury. The results also suggest that rehabilitation programs after ACLR should specifically target the quadriceps and gastrocnemius muscles to reduce lower-limb asymmetries.

Keywords: ACL reconstruction; Return to sport; Gait analysis; Musculoskeletal simulation; Electromyography; Injury risk index

1. Introduction

Professional football players who have undergone anterior cruciate ligament (ACL) reconstruction are more likely to sustain an ACL injury in both the ipsilateral and contralateral limbs than players who have never had an ACL injury (Clark et al., 2019). Individuals with ACL reconstruction (ACLR) usually exhibit abnormal gait patterns (de Oliveira et al., 2019), which may persist for more than 12 months after surgery (Esmaeili et al., 2026), and lower-limb asymmetries have been reported as important factors that may be linked to an increased risk of ACL injury (Mazumder et al., 2019). To improve injury prevention and rehabilitation programs, various test procedures have been proposed to determine whether an athlete is ready to return to sport after ACLR; however, these procedures typically lack validation (Bates et al., 2019). *In vivo* biomechanical video analyses and musculoskeletal simulations provide information on parameters that cannot be measured directly in experiments, which may help determine whether athletes are adequately prepared to return to activity or whether deficiencies are still present (Lanier et al., 2020). Therefore, there remains a need to develop effective screening procedures to identify athletes at risk of a secondary ACL injury. Moreover, previous studies have indicated that biomechanical and neuromuscular risk factors for ACL injury can be modified by training interventions, which may help in developing successful injury prevention programs (Eberle et al., 2019).

Gait analysis has been used to identify asymmetries of ACLR limbs compared with contralateral and healthy control limbs (Bulat et al., 2019; Mantashloo et al., 2020; Webster & Hewett, 2019). Temporal characteristics of knee kinetics and quadriceps EMG during gait have also revealed neuromuscular deficits in the involved limb, some of which were still present 24 months after ACLR (Ito et al., 2022). Asymmetries between the dominant and non-dominant legs in several biomechanical and neuromuscular parameters, such as knee joint kinematics and kinetics, lower-limb muscle activation, and knee joint instability, have been reported in the literature (Ali et al., 2017; Bourne et al., 2019; Dashti Rostami et al., 2020; de Oliveira et al., 2019; Kuszewski et al., 2019; Nedergaard et al., 2020; Samaan et al., 2018). Several authors have reported higher knee joint loads and internal knee extension moments after ACL injury, which have been linked to joint instability and were alleviated after ACLR (Blackburn et al., 2019; Lin & Sigward, 2020; Pietrosimone et al., 2019). Previous electromyography (EMG) and vertical ground reaction force (VGRF) assessments showed that quadriceps–hamstring co-activation and bilateral muscle activation increased knee loading after ACLR (Dashti Rostami et al., 2020). In addition, lower-limb muscle activity after ACLR was found to be lower in the injured leg than in the contralateral and control limbs (Hall et al., 2015). Although risk factors related to lower-limb asymmetries have been investigated previously, the relationship between knee joint gait parameters and ACL loading after reconstruction remains unclear (Kotsifaki et al., 2022; Maniar et al., 2022).

Current return-to-sport tests cannot guarantee the prevention of ACL re-injury, since athletes may return to their pre-injury activity level after inadequate recovery from ACLR. Only one-third of athletes return to full competition one year after ACLR (Smale et al., 2020; Ueno et al., 2020; Webster & Feller, 2019; Webster & Hewett, 2019). Young athletes who pass return-to-sport tests after ACLR have a 30- to 40-fold greater risk of a second ACL injury than athletes without a history of ACL injury (Dashti Rostami et al., 2020). A meta-analysis showed that passing return-to-sport test batteries reduced the risk of subsequent ACL graft rupture by 60% but increased the risk of contralateral ACL injury by 235% (Webster & Hewett, 2019). Moreover, passing standard return-to-sport tests may not guarantee that high-performing athletes have met the rehabilitation requirements after ACLR (Marigi et al., 2019; Nawasreh et al., 2018). Therefore, assessing athletes' readiness to return to sport remains challenging, because no standard objective measures exist for this purpose (Bates et al., 2017; Bulat et al., 2019).

Secondary ACL injuries are common. A meta-analysis reported a total second ACL injury rate of 15% after ACLR, which increased to 23% among athletes younger than 25 years who returned to sport (Wiggins et al., 2016). In football specifically, a recent meta-analysis of 34 studies (16,905 players) reported a pooled second ACL injury incidence of 21.6%, with contralateral (10.6%) and ipsilateral (10.4%) injuries of similar magnitude (López Personat et al., 2026). In a cohort of 862 soccer players reconstructed with hamstring tendon autografts, graft rupture and contralateral ACL rupture occurred in 10% and 8% of players, respectively, within 5 years, and return to soccer was a risk factor for further ACL injury (Manara et al., 2022); younger age and returning to play have also been associated with a higher likelihood of subsequent ACLR in football players (Fältström et al., 2025). Moreover, although approximately 72% of soccer players return to play after ACLR, only 53% return to their pre-injury level (Manojlović et al., 2024). Criteria-based return-to-sport decisions can reduce this risk. In the Delaware–Oslo ACL cohort, returning to level I sports was associated with a 4.3-fold higher knee reinjury rate, and the reinjury rate decreased by 51% for each month that return to sport was delayed up to 9 months after surgery; more symmetrical quadriceps strength before return also reduced the reinjury rate (Grindem et al., 2016). Similarly, among male professional athletes, not meeting six clinical discharge criteria before returning to sport was associated with a four-fold greater risk of ACL graft rupture, and a lower hamstring-to-quadriceps strength ratio was also associated with an increased risk (Kyritsis et al., 2016). Nevertheless, the evidence supporting specific criteria remains limited: patients who sustained a second ACL injury returned to sport only about 25 days earlier than those who did not, with very low certainty

of evidence and no such difference among professional athletes (Piussi et al., 2024), and a recent clinical practice guideline concluded that there is no evidence on which progression or discharge criteria should be used (Kotsifaki et al., 2023). Furthermore, these criteria are based on strength and hop performance and do not directly quantify the mechanical load transmitted to the ACL. A systematic review showed that athletes still present functional and biomechanical deficits at the time of return-to-sport clearance, which traditional strength and hop tests are unable to identify accurately (Gill et al., 2024). Indeed, musculoskeletal modeling has shown that athletes cleared for return to sport after ACLR may still exhibit between-limb asymmetry in ACL forces during running and cutting (Kotsifaki et al., 2022), as well as lower quadriceps and patellofemoral joint contact forces in the reconstructed limb during side-step cutting (San Jose et al., 2023).

Biomechanical simulations based on *in vivo* tests provide a powerful tool for characterizing ACL loading (Dewig et al., 2022; Nedergaard et al., 2020; Webster & Hewett, 2019; Wu et al., 2018). One such open-source platform is OpenSim, which allows users to develop musculoskeletal models and perform dynamic simulations of movement, including hypothetical "what-if" scenarios (Mantashloo et al., 2020). OpenSim enables the study of joint loading, muscle activation, neuromuscular coordination, and athletic performance, as well as many other predictive analyses. For example, Sharifi and Shirazi-Adl (2021) examined the effects of alterations in knee flexion and muscle activation on the stability of the ACL-deficient knee joint using finite element and OpenSim simulations. A comprehensive understanding of the risk factors related to ACL loading is required to design more effective ACL re-injury prevention approaches (Dai et al., 2014; Wu et al., 2018). Therefore, there is an urgent need to develop predictive approaches for estimating ACL loading after ACLR and identifying the risk factors related to it.

The aim of this study was to investigate the relationship between knee joint kinematic and kinetic parameters and ACL loading in the dominant and non-dominant legs of professional football players with a history of one ACLR, using gait analysis, lower-limb muscle activation measurements, and musculoskeletal simulation. A further aim was to propose a new return-to-sport procedure by introducing an index for predicting the risk of ACL re-injury and a rehabilitation program that compensates for changes in muscle activation forces after ACLR. We hypothesized that lower-limb asymmetries after ACL reconstruction are directly related to increased ACL loading and, consequently, an increased risk of ACL re-injury.

2. Methods

2.1. Data collection and preprocessing

Six professional male football players (age: 23.7 ± 1.8 years; height: 182.2 ± 6.3 cm; mass: 73.3 ± 7.9 kg; mean ± SD) voluntarily participated in this study. The study protocol was approved by the institutional research ethics committee, and all participants provided written informed consent prior to participation. The subjects were divided into two groups: an ACLR group (n = 3), consisting of players with one ACLR using a hamstring tendon autograft, and a control group (n = 3), consisting of players without any history of lower-limb musculoskeletal injury. The ACLR subjects were tested 9 to 20 months after surgery; they had fully recovered and returned to their usual sports activities. All three ACLR subjects had injured the ACL of their dominant leg. The demographic characteristics of the subjects are provided in Table 1. All subjects wore running shoes and performed normal overground walking at a self-selected speed in the Gait Analysis Laboratory of the Mowafaghian Research Centre of Intelligent Neuro-Rehabilitation Technologies.

Table 1. Demographic characteristics of the subjects.

Subject	Group	Age (years)	Height (cm)	Mass (kg)	Dominant leg	Time after ACLR (months)
1	ACLR	23	183	76	Right	20
2	ACLR	23	184.5	64	Left	16
3	ACLR	25	191	87	Left	9
4	Control	21	182	74	Right	–
5	Control	26	171.5	69	Right	–
6	Control	24	181	70	Left	–

Following the Helen Hayes lower-limb (Plug-in Gait) marker set (Kadaba et al., 1989; Kar & Quesada, 2012; Shi et al., 2020), 20 reflective markers were attached to each subject's body (Bates et al., 2017). Marker trajectories were recorded at 100 Hz using a three-dimensional motion capture system with 10 cameras (Vicon, Oxford, UK) and post-processed using the Vicon software. Ground reaction forces (GRFs) were recorded synchronously at 1000 Hz using two force plates. EMG and maximum voluntary contraction (MVC) data were recorded from both legs at 1000 Hz using an eight-channel wireless EMG system (MyoWare). Electrodes were placed on four muscles of each leg, namely the biceps femoris, rectus femoris, vastus lateralis, and gastrocnemius medialis (Kar & Quesada, 2013). To obtain the MVC of the gastrocnemius medialis, the subjects stood on the test leg with the knee extended, holding a stable object for balance, and performed a maximal voluntary plantar flexion. For the rectus femoris, the subjects lay in the prone position with the knee flexed and performed a maximal isometric knee extension against manual resistance applied by the examiner. For the biceps femoris and vastus lateralis, the subjects were seated with 90° of hip flexion, with the torso and hips strapped to the seat, and performed maximal isometric knee flexion and knee extension, respectively, against manual resistance applied by the examiner. For each subject, complete stance and swing phases of the gait cycle for both the right and left limbs were captured in three successful trials at a self-selected speed over the two force plates. Figure 1 shows one of the subjects during a gait trial.



Figure 1. One of the subjects during a gait trial.

Marker trajectories and GRF data were preprocessed using a zero-phase first-order moving-average filter with window widths of 30 and 20 samples, respectively, followed by a zero-lag second-order low-pass Butterworth filter with a cutoff frequency of 16 Hz. The EMG data were first detrended using the

MATLAB detrend function to remove the DC offset and linear trend, and were then filtered with a zero-phase digital filter applied in the forward and reverse directions. The filtered signal was full-wave rectified by taking its absolute value, and a zero-lag fourth-order low-pass Butterworth filter with a cutoff frequency of 5 Hz was applied to obtain the linear envelope. The resulting envelope was normalized to its root mean square (RMS) value (Ueno et al., 2020). Because EMG amplitudes depend on subject-specific factors, such as skin–electrode impedance, subcutaneous tissue thickness, and electrode placement, recordings can differ between subjects even for the same muscle and the same movement. Therefore, the EMG signals were also normalized to the MVC to reduce this variability and allow comparisons between subjects.

2.2. Musculoskeletal model

Muscle activations and forces, knee joint kinematic and kinetic parameters, and ACL loading were estimated through musculoskeletal modeling in OpenSim (version 4.1), an open-source software platform for modeling and simulating movement (Delp et al., 2007). The model used in this study was based on the generic three-dimensional Gait2354 musculoskeletal model developed by Thelen and colleagues and distributed with OpenSim. This model is a simplified version of the Gait2392 model, which has 23 degrees of freedom and 92 musculotendon actuators representing 76 muscles of the lower extremities and torso; in Gait2354, the musculature is reduced to 54 musculotendon actuators representing 46 muscles to improve simulation speed. In this study, the ACL was added to the knee joint and modeled using two ligament elements representing the anteromedial (aACL) and posterolateral (pACL) bundles (Marieswaran, Jain, et al., 2018), following the extended OpenSim knee model of Marieswaran, Sikidar, et al. (2018). The intact ACL bundles were used for the control group, whereas for the ACLR group the rest length of the bundles was set according to the hamstring graft (Ramkumar et al., 2018). The experimental marker and GRF data were then applied to the OpenSim musculoskeletal model.

Before scaling the model, 10 virtual markers were added to the preprocessed experimental marker data in MATLAB to improve simulation accuracy by providing additional anatomical reference points. These markers were placed at the mid-ASIS, mid-pelvis, toe–ground (left and right), heel–ground (left and right), mid-knee (left and right), and mid-ankle (left and right) locations, and the position of each was computed as the midpoint of the line connecting two existing markers. The generic model was then scaled to the anthropometry of each subject using the skin markers placed on bony landmarks during a static reference trial, to ensure that each subject-specific model was accurate. The modified OpenSim musculoskeletal model developed in this study is shown in Figure 2.

For each trial, inverse kinematics (IK) analysis was used to calculate the joint angles, and inverse dynamics (ID) analysis was performed to calculate the net joint forces and moments; the results of these two analyses were used in the subsequent steps. The residual reduction algorithm (RRA) was then used to minimize the effects of modeling and marker-data processing errors, which accumulate and lead to large non-physical compensatory forces known as residuals. RRA adjusts the torso mass center of the subject-specific model and allows the joint kinematics obtained from IK to vary slightly so that they are more dynamically consistent with the measured GRF data. Subsequently, static optimization was used to estimate the muscle activations and forces and the ACL loads by minimizing the sum of squared muscle activations at each time frame. Static optimization is an extension of inverse dynamics that resolves the net joint moments into individual muscle forces at each time instant. Finally, a joint reaction force (JRF) analysis was performed for the knee to calculate the forces and moments transferred between consecutive bodies as a result of all loads acting on the model. To assess the consistency of the estimated knee joint contact forces, the results were compared across all trials performed by each subject throughout each activity cycle.

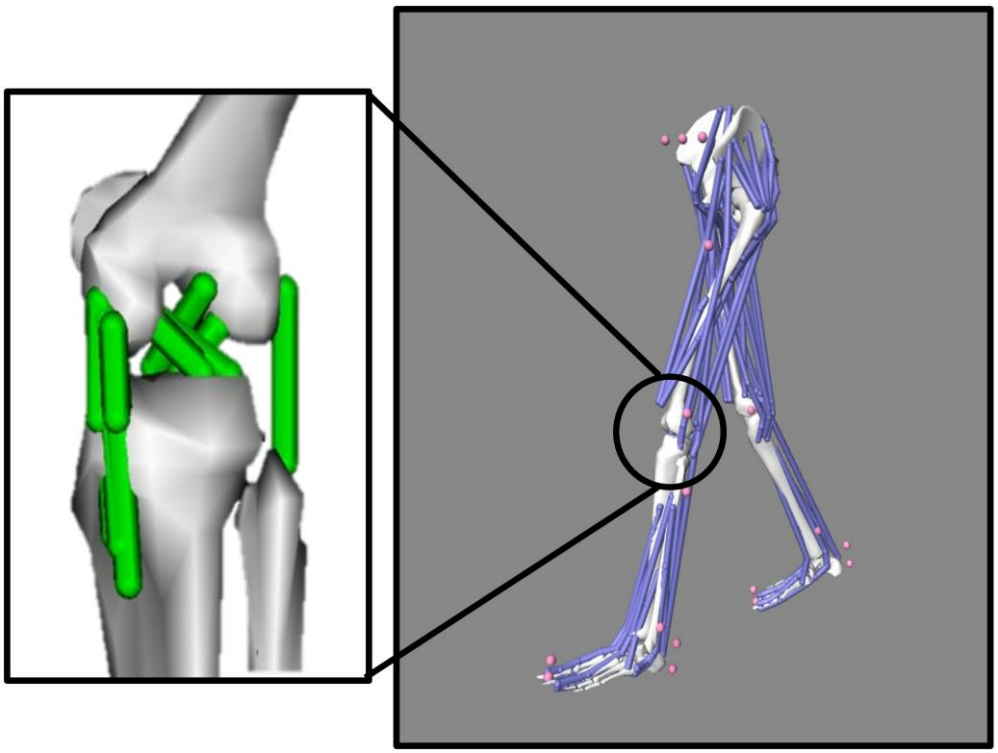


Figure 2. The modified OpenSim musculoskeletal model used in this study. The inset shows an enlarged view of the knee joint with the ligament elements (green).

2.3. Statistical analyses

Knee contact forces and flexion angles were analyzed in three dimensions. All forces were normalized to body weight (BW) (Wannop et al., 2012), and the knee contact forces and angles were time-normalized to 100% of the gait cycle to allow comparisons between subjects. Muscle forces were obtained for four muscles in each leg (eight muscles in total) and normalized to body weight. The ACL forces (aACL and pACL) were then calculated for each subject in both groups (control and ACLR). Asymmetries in the subjects with ACLR were identified by comparing the knee flexion angle, the knee contact force, and the mean maximum muscle activation obtained from both the simulations and the EMG measurements. Differences between the ACLR and control groups in the peak knee flexion angle and the IRI were assessed using two-tailed independent-samples t-tests, with the level of significance set at $p < 0.05$. All statistical analyses were performed in MATLAB and OriginPro.

2.4. Injury risk index

To develop an index for assessing the risk of a second ACL injury in professional football players after reconstruction, the maximum ACL force during the gait cycle, calculated by the OpenSim simulation, was compared with the ultimate tensile load of the intact ACL, which has been reported to be 2160 N (Woo et al., 1991). Accordingly, the ACL injury risk index (IRI) was calculated as a percentage:

$$\text{IRI}\ (\%) = \frac{\max(F_{\text{ACL}})}{F_{\text{ult}}} \times 100 = \frac{\max(F_{\text{ACL}})}{2160\ \text{N}} \times 100 \quad (1)$$

where $\max(F_{\text{ACL}})$ is the maximum ACL force during the gait cycle and $F_{\text{ult}} = 2160$ N is the ultimate tensile load of the intact ACL.

The proposed criterion for classifying the ACL health status of the injured leg based on the IRI is shown in Figure 3. The ultimate tensile load of the patellar tendon autograft, which is commonly used to reconstruct the injured ACL, has been reported to be 1580 N (Shani et al., 2016). Although other autografts with higher ultimate tensile loads are also used for ACLR, the ultimate tensile load of the

patellar tendon autograft was used in this study to ensure that the proposed criterion is conservative. Therefore, ACL re-injury of the injured leg after ACLR may occur when the IRI reaches 73% (i.e., 1580/2160). Rupture of the ACL autograft was considered the only source of ACL re-injury after ACLR, and other sources of re-injury were neglected in this study. Accordingly, the range below failure was divided into three zones: a safe zone with a safety factor of at least 3 (IRI < 24%), a low-risk zone with a safety factor of 1.5 to 3 (24% ≤ IRI < 48%), and a high-risk zone with a safety factor of 1 to 1.5 (48% ≤ IRI < 73%). If the IRI of a player falls in the high-risk zone, it is suggested that the player discontinue regular training and undergo additional recovery activities at the physician's discretion.

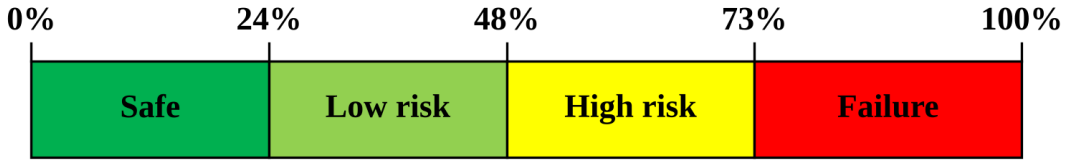


Figure 3. Proposed criterion for classifying the ACL health status of the injured (reconstructed) leg based on the injury risk index (IRI).

A similar IRI criterion can be defined for the contralateral leg, for which failure occurs at 100% because the player's ACL is assumed to be intact. The proposed criterion for the contralateral leg is shown in Figure 4. In this case, the entire IRI range was likewise divided into a safe zone (safety factor ≥ 3; IRI < 33%), a low-risk zone (safety factor 1.5–3; 33% ≤ IRI < 66%), and a high-risk zone (safety factor 1–1.5; 66% ≤ IRI < 100%).

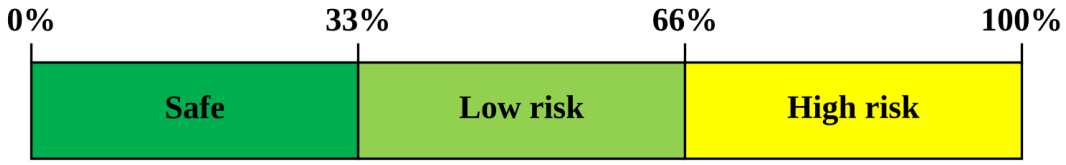


Figure 4. Proposed criterion for classifying the ACL health status of the contralateral leg based on the injury risk index (IRI).

2.5. Return-to-sport procedure

A new return-to-sport procedure for football players after ACLR is proposed in this study and is shown schematically in Figure 5. This procedure is specific to football players and is expected to provide a more accurate assessment because it accounts for ACL loading, which has not been considered in previous procedures. In addition to the status of the injured leg, the procedure also assesses the status of the contralateral leg. This is important because previous studies have shown that both legs of patients with ACLR may be at a higher risk of injury (Dashti Rostami et al., 2020; Sharifi & Shirazi-Adl, 2021; Smale et al., 2020). Unlike most previous rehabilitation programs, which did not address the balance of muscle activation forces, the proposed procedure includes an examination of changes in muscle activation forces after ACLR. Such changes may lead to lower-limb asymmetries after ACLR, which may increase the ACL force and, consequently, the risk of ACL re-injury. Accordingly, a specific rehabilitation program should be designed for both the injured and contralateral legs of each athlete.

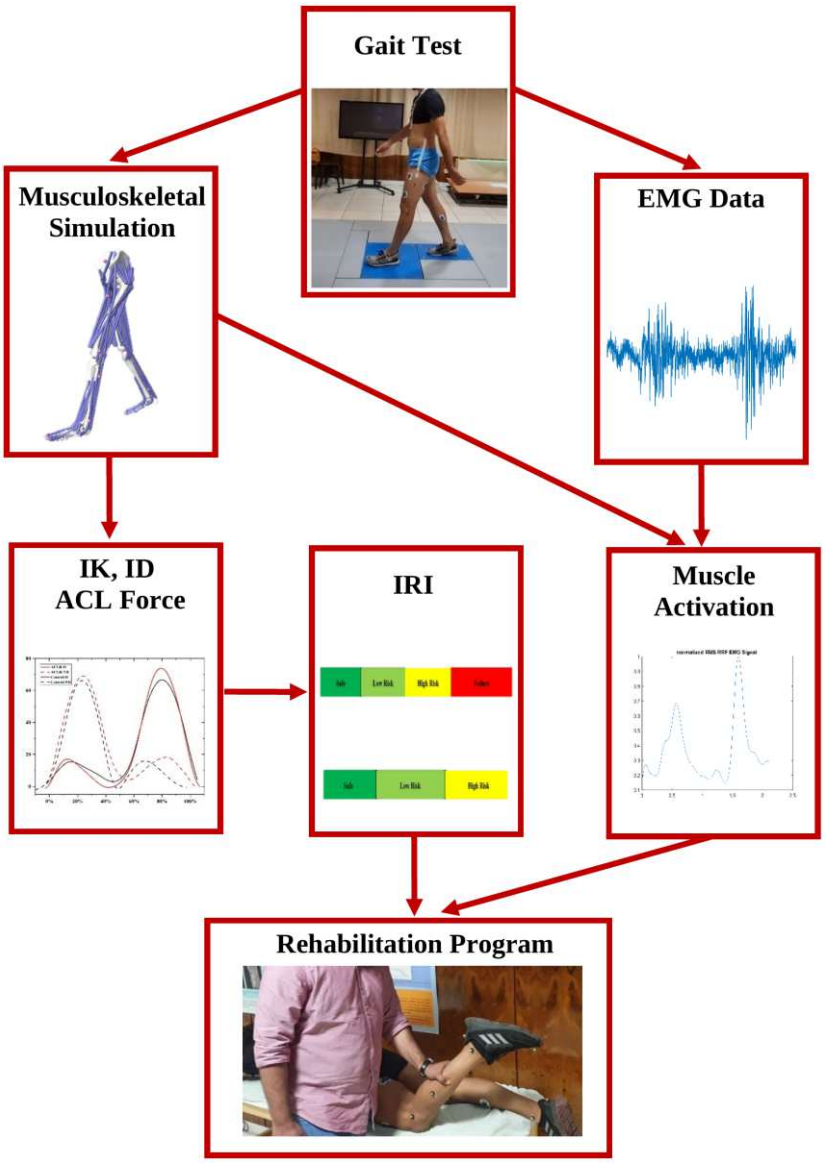


Figure 5. Schematic illustration of the proposed return-to-sport procedure. EMG: electromyography; IK: inverse kinematics; ID: inverse dynamics; IRI: injury risk index.

3. Results

Figure 6 compares the mean knee flexion angles of the dominant (injured) and non-dominant (contralateral) legs between the ACLR and control groups. The difference in peak knee flexion angle (PKFA) during the gait cycle between the ACLR and control groups was significant for the dominant (injured) leg after return to sport ($p = 0.0015$) but not for the non-dominant (contralateral) leg ($p = 0.15$).

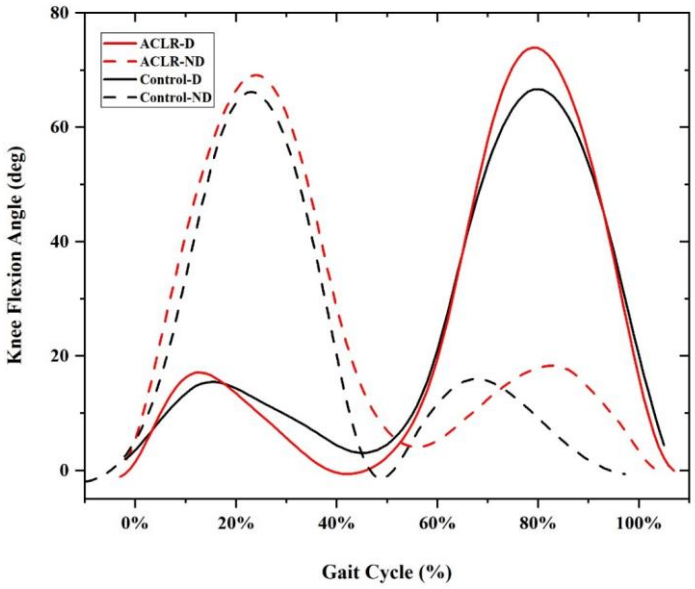


Figure 6. Mean knee flexion angle during the gait cycle for the dominant (D) and non-dominant (ND) legs of the ACLR and control groups.

Figure 7 compares the mean knee contact forces of the dominant and non-dominant legs between the ACLR and control groups. In both groups, the contact force exerted by the tibia on the femur was more than 1 BW higher in the non-dominant leg than in the dominant leg. The peak knee contact force was also approximately 0.5 BW higher in the ACLR group than in the control group in both the injured and contralateral legs.

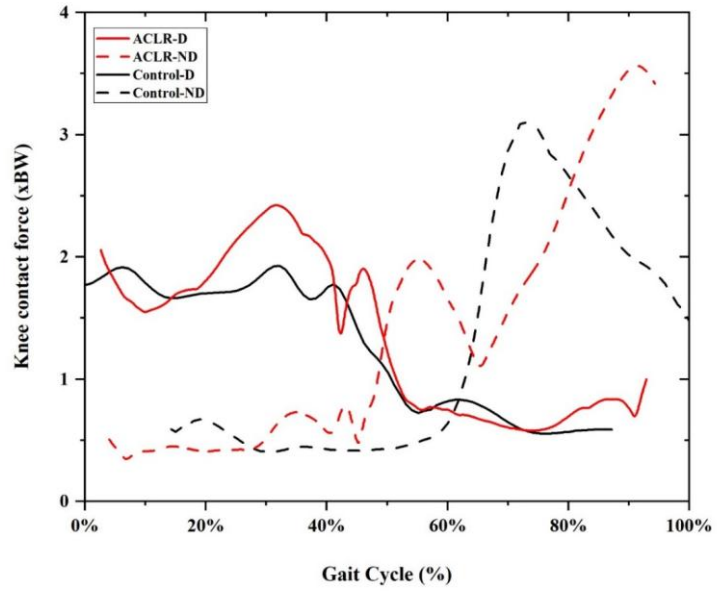


Figure 7. Mean knee contact force (in body weight, BW) during the gait cycle for the dominant (D) and non-dominant (ND) legs of the ACLR and control groups.

To assess the effect of ACLR on knee loading and muscle activity in more depth, the muscle forces obtained from the OpenSim simulation, the EMG data, and the knee contact forces were compared.

Figures 8 and 9 show the muscle forces obtained from the OpenSim simulation for the control and ACLR groups, respectively, and Figures 10 and 11 show the corresponding muscle activations measured by EMG. Overall, the OpenSim and EMG results showed similar trends in muscle activity in both groups. Compared with the control group, the ACLR group showed higher biceps femoris and vastus lateralis activity but lower rectus femoris and gastrocnemius activity in the dominant (injured) leg during the gait cycle. Figures 8 and 10 also show that the subjects in the control group had higher biceps femoris, vastus lateralis, and gastrocnemius medialis activity and lower rectus femoris activity in their dominant leg than in their non-dominant leg. In contrast, Figures 9 and 11 show that the subjects in the ACLR group had higher biceps femoris, vastus lateralis, and rectus femoris activity and lower gastrocnemius medialis activity in their dominant (injured) leg than in their non-dominant leg.

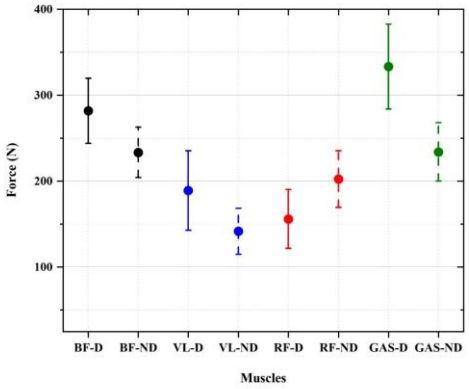


Figure 8. Muscle forces estimated by the OpenSim simulation for the control group. BF: biceps femoris; VL: vastus lateralis; RF: rectus femoris; GAS: gastrocnemius medialis; D: dominant leg; ND: non-dominant leg.

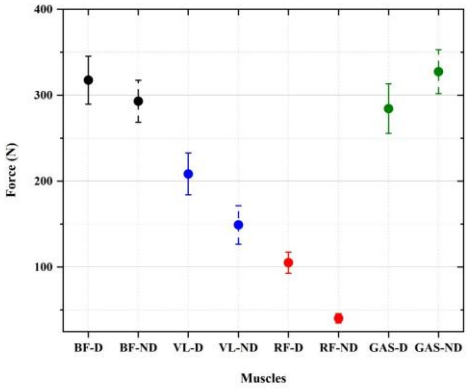


Figure 9. Muscle forces estimated by the OpenSim simulation for the ACLR group. BF: biceps femoris; VL: vastus lateralis; RF: rectus femoris; GAS: gastrocnemius medialis; D: dominant leg; ND: non-dominant leg.

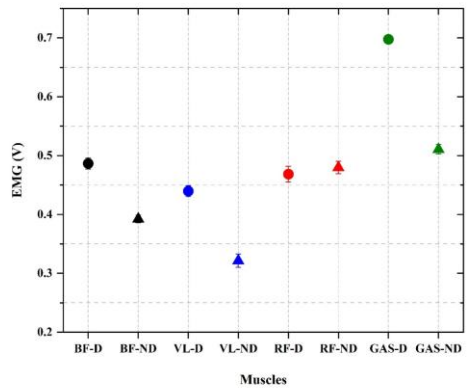


Figure 10. Muscle activation measured by EMG for the control group. BF: biceps femoris; VL: vastus lateralis; RF: rectus femoris; GAS: gastrocnemius medialis; D: dominant leg; ND: non-dominant leg.

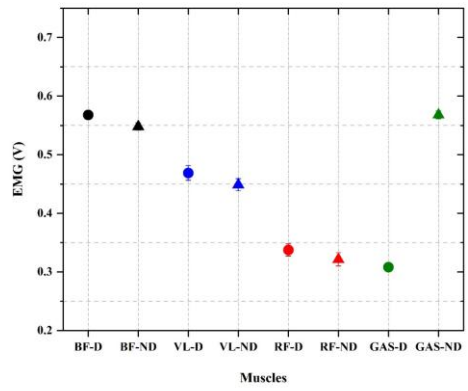


Figure 11. Muscle activation measured by EMG for the ACLR group. BF: biceps femoris; VL: vastus lateralis; RF: rectus femoris; GAS: gastrocnemius medialis; D: dominant leg; ND: non-dominant leg.

The risk of ACL re-injury for the subjects tested in this study was estimated using the proposed IRI, based on the maximum ACL force obtained from the musculoskeletal simulation. Figure 12 shows the mean and standard deviation of the IRI for the aACL and pACL bundles in the dominant and non-dominant legs of the ACLR and control groups. All players who participated in this study were in the safe zone; however, the IRI was significantly higher in the ACLR group than in the control group for both the aACL

(p = 0.015) and pACL (p = 0.006) bundles. The mean IRI values of the ACLR group (approximately 17% for the dominant leg and 22% for the non-dominant leg) were relatively close to the lower bounds of the corresponding low-risk zones (24% for the injured leg and 33% for the contralateral leg).

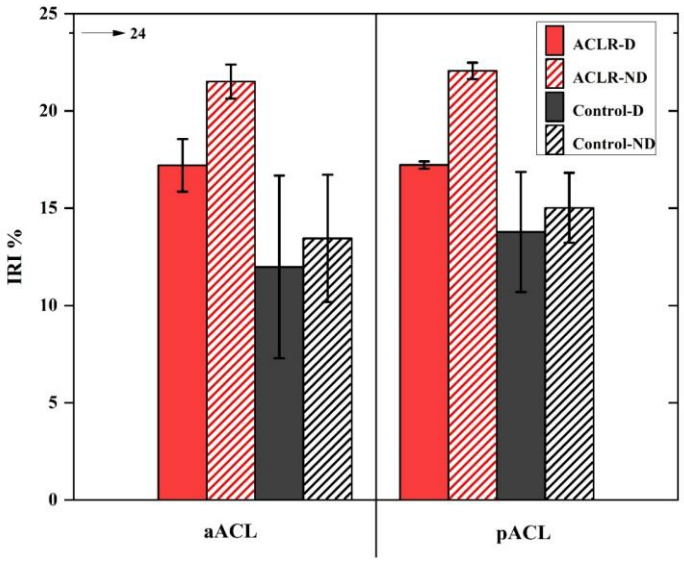


Figure 12. Mean and standard deviation of the injury risk index (IRI) of the aACL and pACL bundles for the dominant (D) and non-dominant (ND) legs of the ACLR and control groups. The arrow indicates the lower bound of the low-risk zone for the injured leg (24%).

4. Discussion and implications

A PKFA range of 60° to 65° has been reported for healthy males during gait (Charles et al., 2021), which is close to the results presented in Figure 6. Figure 6 also shows that, even after return to sport, a limb asymmetry remained in the gait pattern; such asymmetry may increase the risk of ACL re-injury and should be taken into account in return-to-sport procedures and rehabilitation programs. A recent meta-analysis reported smaller peak knee flexion angles during the stance phase of walking in individuals with ACLR than in healthy controls, which persisted beyond 12 months after surgery (Esmaeili et al., 2026). In contrast, the greater PKFA observed in the ACLR group in the present study occurred during the swing phase (approximately 80% of the gait cycle; Figure 6); differences in the gait phase analyzed, together with the small sample size, may explain this discrepancy.

In both the ACLR and control groups, the contact force exerted by the tibia on the femur was higher in the non-dominant leg than in the dominant leg. This difference may be due to muscle weakness in the non-dominant leg. In addition, the difference in peak knee contact force between the two groups may be related to changes in muscle activation after ACLR. A similar knee contact force for young healthy males was reported in a previous study using OpenSim musculoskeletal simulation (Aghdam et al., 2022), and a previous study has also shown that the knee contact force increases after ACLR (Palmieri-Smith et al., 2019). However, comparisons between the dominant (injured) and non-dominant (contralateral) legs have received limited attention in the literature.

A variation in muscle activation trends between the control and ACLR groups similar to that observed in Figures 8–11 was reported in a previous study (Palmieri-Smith et al., 2019). These findings suggest that the increased asymmetry of the knee contact force after return to sport in the ACLR group may be due to changes in muscle activity. Based on the results presented in Figures 8–11, additional rehabilitation

training that balances the activity of the rectus femoris and gastrocnemius muscles may be recommended. Previous studies have also noted that muscle weakness after ACLR is an important factor to consider when optimizing return-to-sport rehabilitation programs (Jenkins et al., 2022; Perry et al., 2022; Rambaud et al., 2022).

From a mechanical perspective, the quadriceps and gastrocnemius can increase ACL loading by inducing anterior tibial shear, particularly when the knee is extended, whereas the hamstrings can unload the ACL by generating posterior tibial shear when the knee is flexed beyond approximately 20°–30° (Maniar et al., 2022). Modeling of ACL-deficient gait has also shown that increasing hamstring force is more effective than reducing quadriceps force in limiting anterior tibial translation (Shelburne et al., 2005). Therefore, the higher biceps femoris activity and the lower rectus femoris and gastrocnemius activity observed in the injured leg of the ACLR group may reflect a protective neuromuscular strategy, as also suggested by Palmieri-Smith et al. (2019), and may partly explain why the IRI of the injured leg was lower than that of the contralateral leg, in which gastrocnemius activity was higher. Conversely, the contralateral leg may be exposed to greater ACL loading, which is in line with reports that contralateral ACL injuries after ACLR are as frequent as graft ruptures, including in football players (López Personat et al., 2026; Manara et al., 2022; Wiggins et al., 2016). Notably, the hamstring-to-quadriceps strength ratio was not associated with second ACL injury after accounting for prognostic factors in a cohort of 574 patients (Högberg et al., 2024), suggesting that isolated strength ratios may not capture the task-specific neuromuscular strategies that determine ACL loading during functional activities.

The increase in ACL force in the ACLR group may be explained by changes in muscle activation and force and in knee contact force after ACLR. Altered muscle activation and force may change the knee contact force and, consequently, the net load transferred to passive structures such as the ligaments and menisci to maintain knee stability. The mean IRI was also higher in the non-dominant (contralateral) leg in both the control and ACLR groups, which may be due to the higher knee contact forces that resulted in higher ACL loading. Moreover, the mean IRI was slightly higher for the simulated pACL bundle than for the aACL bundle. The IRI values obtained for the ACLR and control football players are consistent with previous findings indicating an increased risk of ACL injury in both the dominant and non-dominant legs after ACLR (Sharifi & Shirazi-Adl, 2021).

The magnitudes of the ACL forces estimated in this study are consistent with those reported in previous modeling studies of walking. The IRI values of approximately 12% to 22% (Figure 12) correspond to peak bundle forces of approximately 260 to 475 N, which are of the same order of magnitude as the peak ACL force of 303 N predicted for normal level walking by Shelburne et al. (2004); in that study, the peak occurred in early stance and was mainly determined by the anterior pull of the patellar tendon on the tibia. Furthermore, using an EMG-constrained musculoskeletal modeling approach, Kotsifaki et al. (2022) found that athletes who had been cleared to return to sport after ACLR still exhibited significantly higher ACL forces in the uninvolved limb than in the involved limb during cutting and running, and concluded that current discharge criteria did not ensure the restoration of symmetric loading. Similarly, female elite handball and soccer players with a previous ACL injury still unloaded their ipsilateral knee during side-step cutting approximately 4 years after injury, whereas contralateral knee loading was similar to that of injury-free players (Mausehund & Krosshaug, 2024). These findings are consistent with the higher IRI values observed in the non-dominant (contralateral) leg of the ACLR group in the present study, and support the inclusion of the contralateral leg in the proposed return-to-sport procedure.

The proposed IRI is not intended to replace established return-to-sport criteria, such as limb symmetry in quadriceps strength and hop performance (Grindem et al., 2016; Kyritsis et al., 2016), but rather to complement them by providing a direct estimate of the mechanical demand on the ACL graft and on the contralateral ACL. Because traditional strength and hop tests may not identify persisting deficits at the

time of return to sport (Gill et al., 2024), and symmetric performance in functional tests does not necessarily indicate symmetric ACL loading (Kotsifaki et al., 2022), combining the IRI with existing criteria may provide a more comprehensive assessment of an athlete's readiness to return to sport.

The limitations of this study should be considered before drawing conclusions. First, only three subjects were included in each group; the present results should therefore be regarded as preliminary findings of a pilot study, and the statistical comparisons should be interpreted with caution. Second, the IRI was evaluated during level walking, which is a low-demand task, whereas most non-contact ACL injuries in football occur during high-demand maneuvers such as cutting, landing, and sudden deceleration (Dai et al., 2014). Thus, the IRI values obtained here reflect ACL loading during an everyday activity rather than during injury-risk tasks, and future studies should apply the proposed index to sport-specific tasks such as side-cutting and single-leg landing, including unanticipated tasks with a neurocognitive challenge, during which male elite soccer players with ACLR have shown less favorable knee biomechanics than controls (Gholipour Aghdam et al., 2024). Nevertheless, even knee biomechanics during cutting were not associated with future secondary ACL injury in a large prospective cohort (Mausehund & Krosshaug, 2024), underscoring the multifactorial nature of re-injury risk. Third, the players walked at a self-selected speed, which may have varied between trials. Fourth, all ACLR subjects had injured their dominant leg, so the effects of limb dominance and of the injury itself could not be fully separated.

Fifth, all subjects in the ACLR group received hamstring tendon autografts; since graft type may influence gait mechanics, the findings may not be directly generalizable to patients with other graft types. In addition, the failure threshold of the IRI was based on the ultimate tensile load of a patellar tendon autograft at the time of implantation. After implantation, tendon grafts undergo a remodeling process termed "ligamentization", and ultrastructural differences from the native ACL persist, with no agreement on the time frame of this process (Claes et al., 2011); the actual strength of the grafts 9 to 20 months after surgery may therefore differ from the value used here. Sixth, muscle forces were estimated using static optimization, which minimizes muscle activation and may therefore underestimate antagonist co-contraction, and the generic Gait2354 model was not validated against subject-specific imaging data. Moreover, the rest length of the ACL autograft was set to the same value for all ACLR subjects; future studies could use subject-specific autograft rest lengths measured, for example, by magnetic resonance imaging (MRI), as well as EMG-informed modeling approaches (Kotsifaki et al., 2022). Overall, further research involving more athletes, different types of autografts, and sport-specific tasks may make the proposed IRI more comprehensive and generalizable for return-to-sport assessment after ACLR.

5. Conclusions

Understanding how ACL loading changes after ACLR, as a risk factor for ACL re-injury, and how it relates to knee contact force and muscle activation may help in developing a reliable injury risk index and a return-to-sport procedure for preventing a second ACL injury. The results of this study showed a greater knee flexion angle in the ACLR group and asymmetries between the dominant and non-dominant legs. Furthermore, higher biceps femoris and vastus lateralis activity and lower rectus femoris and gastrocnemius activity were observed in the injured leg after ACLR. These differences in hamstring, quadriceps, and gastrocnemius activation indicate that the rehabilitation of the quadriceps (particularly the rectus femoris) and gastrocnemius muscles after reconstruction may have been inadequate. Changes in muscle activation and force after ACLR may lead to lower-limb asymmetries, which may in turn increase the ACL force and the risk of ACL re-injury. An injury risk index based on the maximum ACL force during the gait cycle was proposed in this study to identify players at risk of re-injury. The proposed index and return-to-sport procedure may help physicians prescribe specific rehabilitation programs for both the injured and contralateral legs of each player to reduce lower-limb asymmetry and the associated risk of ACL re-injury.

Declarations

Ethics approval and consent to participate

The study protocol was approved by the institutional research ethics committee. All participants were informed about the study procedures and provided written informed consent prior to participation.

Consent for publication

All participants provided consent for the publication of their anonymized data and images. The faces of the participants shown in Figures 1 and 5 have been blurred or cropped to prevent identification.

Competing interests

The authors declare no competing interests.

References

Aghdam, H. A., Haghighat, F., Rezaie, M., Kavyani, M., & Karimi, M. T. (2022). Comparison of the knee joint reaction force between individuals with and without acute anterior cruciate ligament rupture during walking. *Journal of Orthopaedic Surgery and Research*, *17*, 250. https://doi.org/10.1186/s13018-022-03136-y

Ali, A. A., Harris, M. D., Shalhoub, S., Maletsky, L. P., Rullkoetter, P. J., & Shelburne, K. B. (2017). Combined measurement and modeling of specimen-specific knee mechanics for healthy and ACL-deficient conditions. *Journal of Biomechanics*, *57*. https://doi.org/10.1016/j.jbiomech.2017.04.008

Bates, N. A., McPherson, A. L., Nesbitt, R. J., Shearn, J. T., Myer, G. D., & Hewett, T. E. (2017). Robotic simulation of identical athletic-task kinematics on cadaveric limbs exhibits a lack of differences in knee mechanics between contralateral pairs. *Journal of Biomechanics*, *53*. https://doi.org/10.1016/j.jbiomech.2016.12.019

Bates, N. A., Mejia Jaramillo, M. C., Vargas, M., McPherson, A. L., Schilaty, N. D., Nagelli, C. V., Krych, A. J., & Hewett, T. E. (2019). External loads associated with anterior cruciate ligament injuries increase the correlation between tibial slope and ligament strain during in vitro simulations of in vivo landings. *Clinical Biomechanics*, *61*. https://doi.org/10.1016/j.clinbiomech.2018.11.010

Blackburn, T., Pietrosimone, B., Goodwin, J. S., Johnston, C., & Spang, J. T. (2019). Co-activation during gait following anterior cruciate ligament reconstruction. *Clinical Biomechanics*, *67*. https://doi.org/10.1016/j.clinbiomech.2019.05.010

Bourne, M. N., Webster, K. E., & Hewett, T. E. (2019). Is fatigue a risk factor for anterior cruciate ligament rupture? *Sports Medicine*, *49*(11). https://doi.org/10.1007/s40279-019-01134-5

Bulat, M., Korkmaz Can, N., Arslan, Y. Z., & Herzog, W. (2019). Musculoskeletal simulation tools for understanding mechanisms of lower-limb sports injuries. *Current Sports Medicine Reports*, *18*(6). https://doi.org/10.1249/JSR.0000000000000601

Charles, J. P., Fu, F. H., & Anderst, W. J. (2021). Predictions of anterior cruciate ligament dynamics from subject-specific musculoskeletal models and dynamic biplane radiography. *Journal of Biomechanical Engineering*, *143*(3). https://doi.org/10.1115/1.4048710

Claes, S., Verdonk, P., Forsyth, R., & Bellemans, J. (2011). The "ligamentization" process in anterior cruciate ligament reconstruction: What happens to the human graft? A systematic review of the literature. *The American Journal of Sports Medicine*, *39*(11), 2476–2483. https://doi.org/10.1177/0363546511402662

Clark, N., Forshey, T., Mulligan, I., & Kindel, C. (2019). Knee mechanics during a change of direction movement in division I athletes following full return to sport from anterior cruciate ligament reconstruction. *Physical Therapy in Sport*, *35*. https://doi.org/10.1016/j.ptsp.2018.11.008

Dai, B., Mao, D., Garrett, W. E., & Yu, B. (2014). Anterior cruciate ligament injuries in soccer: Loading mechanisms, risk factors, and prevention programs. *Journal of Sport and Health Science*, *3*(4). https://doi.org/10.1016/j.jshs.2014.06.002

Dashti Rostami, K., Alizadeh, M., Minoonejad, H., Thomas, A., & Yazdi, H. (2020). Relationship between electromyographic activity of knee joint muscles with vertical and posterior ground reaction forces in anterior cruciate ligament reconstructed patients during a single leg vertical drop landing task. *Research in Sports Medicine*, *28*(1). https://doi.org/10.1080/15438627.2019.1647204

Delp, S. L., Anderson, F. C., Arnold, A. S., Loan, P., Habib, A., John, C. T., Guendelman, E., & Thelen, D. G. (2007). OpenSim: Open-source software to create and analyze dynamic simulations of movement. *IEEE Transactions on Biomedical Engineering*, *54*(11), 1940–1950. https://doi.org/10.1109/TBME.2007.901024

de Oliveira, E. A., Andrade, A. O., & Vieira, M. F. (2019). Linear and nonlinear measures of gait variability after anterior cruciate ligament reconstruction. *Journal of Electromyography and Kinesiology*, *46*. https://doi.org/10.1016/j.jelekin.2019.03.007

Dewig, D. R., Mills, H. R., Evans-Pickett, A., Pietrosimone, B. G., & Troy Blackburn, J. (2022). Aberrant gait biomechanics in individuals with ACL reconstruction are magnified during treadmill walking. *Journal of Biomechanics*, *134*, 110989. https://doi.org/10.1016/j.jbiomech.2022.110989

Eberle, R., Heinrich, D., van den Bogert, A. J., Oberguggenberger, M., & Nachbauer, W. (2019). An approach to generate noncontact ACL-injury prone situations on a computer using kinematic data of non-injury situations and Monte Carlo simulation. *Computer Methods in Biomechanics and Biomedical Engineering*, *22*(1). https://doi.org/10.1080/10255842.2018.1522534

Esmaeili, A., Jafarnezhadgero, A., Sajedi, H., Aydin, E., Hortobágyi, T., & Granacher, U. (2026). Time-dependent alterations in walking biomechanics after anterior cruciate ligament reconstruction compared with healthy individuals: A systematic review with meta-analysis. *Sports Medicine – Open*, *12*, 39. https://doi.org/10.1186/s40798-026-01016-x

Fältström, A., Forssblad, M., & Sandon, A. (2025). Young age and return to play increase the likelihood of subsequent ACL reconstruction in football players: Data from the Swedish National Knee Ligament Registry. *Knee Surgery, Sports Traumatology, Arthroscopy*, *33*(7), 2368–2378. https://doi.org/10.1002/ksa.12580

Gholipour Aghdam, G. M., Alizadeh, M. H., Minoonejad, H., Shirzad, E., & Wilke, J. (2024). Knee biomechanics during neurocognitively challenged drop landings in male elite soccer players with anterior cruciate ligament reconstruction. *Sports Medicine – Open*, *10*, 19. https://doi.org/10.1186/s40798-024-00685-w

Gill, V. S., Tummala, S. V., Han, W., Boddu, S. P., Verhey, J. T., Marks, L., & Chhabra, A. (2024). Athletes continue to show functional performance deficits at return to sport after anterior cruciate ligament reconstruction: A systematic review. *Arthroscopy*, *40*(8), 2309–2321.e2. https://doi.org/10.1016/j.arthro.2023.12.033

Grindem, H., Snyder-Mackler, L., Moksnes, H., Engebretsen, L., & Risberg, M. A. (2016). Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: The Delaware-Oslo ACL cohort study. *British Journal of Sports Medicine*, *50*(13), 804–808. https://doi.org/10.1136/bjsports-2016-096031

Hall, M., Stevermer, C. A., & Gillette, J. C. (2015). Muscle activity amplitudes and co-contraction during stair ambulation following anterior cruciate ligament reconstruction. *Journal of Electromyography and Kinesiology*, *25*(2). https://doi.org/10.1016/j.jelekin.2015.01.007

Högberg, J., Piussi, R., Wernbom, M., Della Villa, F., Simonsson, R., Samuelsson, K., Thomeé, R., & Hamrin Senorski, E. (2024). No association between hamstrings-to-quadriceps strength ratio and second ACL injuries after accounting for prognostic factors: A cohort study of 574 patients after ACL-reconstruction. *Sports Medicine – Open*, *10*, 7. https://doi.org/10.1186/s40798-023-00670-9

Ito, N., Capin, J. J., Khandha, A., Buchanan, T. S., & Snyder-Mackler, L. (2022). Identifying gait pathology after ACL reconstruction using temporal characteristics of kinetics and electromyography. *Medicine and Science in Sports and Exercise*, *54*(6), 923–930. https://doi.org/10.1249/MSS.0000000000002881

Jenkins, S. M., Guzman, A., Gardner, B. B., Bryant, S. A., del Sol, S. R., McGahan, P., & Chen, J. (2022). Rehabilitation after anterior cruciate ligament injury: Review of current literature and recommendations. *Current Reviews in Musculoskeletal Medicine*, *15*, 170–179. https://doi.org/10.1007/s12178-022-09752-9

Kadaba, M. P., Ramakrishnan, H. K., Wootten, M. E., Gainey, J., Gorton, G., & Cochran, G. V. B. (1989). Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. *Journal of Orthopaedic Research*, *7*(6), 849–860. https://doi.org/10.1002/jor.1100070611

Kar, J., & Quesada, P. M. (2012). A numerical simulation approach to studying anterior cruciate ligament strains and internal forces among young recreational women performing valgus inducing stop-jump activities. *Annals of Biomedical Engineering*, *40*(8), 1679–1691. https://doi.org/10.1007/s10439-012-0572-x

Kar, J., & Quesada, P. M. (2013). A musculoskeletal modeling approach for estimating anterior cruciate ligament strains and knee anterior–posterior shear forces in stop-jumps performed by young recreational female athletes. *Annals of Biomedical Engineering*, *41*(2), 338–348. https://doi.org/10.1007/s10439-012-0644-y

Kotsifaki, A., Van Rossom, S., Whiteley, R., Korakakis, V., Bahr, R., D'Hooghe, P., Papakostas, E., Sideris, V., Farooq, A., & Jonkers, I. (2022). Between-limb symmetry in ACL and tibiofemoral contact forces in athletes

after ACL reconstruction and clearance for return to sport. *Orthopaedic Journal of Sports Medicine*, *10*(4), 1–12. https://doi.org/10.1177/23259671221084742

Kotsifaki, R., Korakakis, V., King, E., Barbosa, O., Maree, D., Pantouveris, M., Bjerregaard, A., Luomajoki, J., Wilhelmsen, J., & Whiteley, R. (2023). Aspetar clinical practice guideline on rehabilitation after anterior cruciate ligament reconstruction. *British Journal of Sports Medicine*, *57*(9), 500–514. https://doi.org/10.1136/bjsports-2022-106158

Kuszewski, M. T., Gnat, R., Szlachta, G., Kaczyńska, M., & Knapik, A. (2019). Passive stiffness of the hamstrings and the rectus femoris in persons after an ACL reconstruction. *Physician and Sportsmedicine*, *47*(1). https://doi.org/10.1080/00913847.2018.1527171

Kyritsis, P., Bahr, R., Landreau, P., Miladi, R., & Witvrouw, E. (2016). Likelihood of ACL graft rupture: Not meeting six clinical discharge criteria before return to sport is associated with a four times greater risk of rupture. *British Journal of Sports Medicine*, *50*(15), 946–951. https://doi.org/10.1136/bjsports-2015-095908

Lanier, A. S., Knarr, B. A., Stergiou, N., Snyder-Mackler, L., & Buchanan, T. S. (2020). ACL injury and reconstruction affect control of ground reaction forces produced during a novel task that simulates cutting movements. *Journal of Orthopaedic Research*, *38*(8). https://doi.org/10.1002/jor.24604

Lin, P. E., & Sigward, S. M. (2020). Influence of hamstrings on knee moments during loading response of gait in individuals following ACL reconstruction. *Journal of Orthopaedic Research*, *38*(2). https://doi.org/10.1002/jor.24465

López Personat, A., Mariscal, G., Stålman, A., Cristiani, R., Von Essen, C., Capurro-Soler, B., Chahla, J., & Sandon, A. (2026). Second ACL injuries in football players after ACL reconstruction: A systematic review and meta-analysis. *Knee Surgery, Sports Traumatology, Arthroscopy*. Advance online publication. https://doi.org/10.1002/ksa.70471

Manara, J. R., Salmon, L. J., Kilani, F. M., de Camino, G. Z., Monk, C., Sundaraj, K., Pinczewski, L. A., & Roe, J. P. (2022). Repeat anterior cruciate ligament injury and return to sport in Australian soccer players after anterior cruciate ligament reconstruction with hamstring tendon autograft. *The American Journal of Sports Medicine*, *50*(13), 3533–3543. https://doi.org/10.1177/03635465221125467

Maniar, N., Cole, M. H., Bryant, A. L., & Opar, D. A. (2022). Muscle force contributions to anterior cruciate ligament loading. *Sports Medicine*, *52*(8), 1737–1750. https://doi.org/10.1007/s40279-022-01674-3

Manojlović, M., Ninković, S., Matić, R., Veršić, Š., Modrić, T., Sekulić, D., & Drid, P. (2024). Return to play and performance after anterior cruciate ligament reconstruction in soccer players: A systematic review of recent evidence. *Sports Medicine*, *54*(8), 2097–2108. https://doi.org/10.1007/s40279-024-02035-y

Mantashloo, Z., Letafatkar, A., & Moradi, M. (2020). Vertical ground reaction force and knee muscle activation asymmetries in patients with ACL reconstruction compared to healthy individuals. *Knee Surgery, Sports Traumatology, Arthroscopy*, *28*(6). https://doi.org/10.1007/s00167-019-05743-5

Marieswaran, M., Jain, I., Garg, B., Sharma, V., & Kalyanasundaram, D. (2018). A review on biomechanics of anterior cruciate ligament and materials for reconstruction. *Applied Bionics and Biomechanics*, *2018*. https://doi.org/10.1155/2018/4657824

Marieswaran, M., Sikidar, A., Goel, A., Joshi, D., & Kalyanasundaram, D. (2018). An extended OpenSim knee model for analysis of strains of connective tissues. *BioMedical Engineering OnLine*, *17*(1), 1–13. https://doi.org/10.1186/s12938-018-0474-8

Marigi, E. M., Bernard, C. D., Hale, R. F., Stuart, M. J., Levy, B. A., Dahm, D. L., Hewett, T. E., & Krych, A. J. (2019). Return to sport: Does 6-month functional testing predict second ACL injuries at long-term follow-up? *Orthopaedic Journal of Sports Medicine*, *7*(7_suppl5). https://doi.org/10.1177/2325967119s00254

Mausehund, L., & Krosshaug, T. (2024). Knee biomechanics during cutting maneuvers and secondary ACL injury risk: A prospective cohort study of knee biomechanics in 756 female elite handball and soccer players. *The American Journal of Sports Medicine*, *52*(5), 1209–1219. https://doi.org/10.1177/03635465241234255

Mazumder, O., Chakravarty, K., Chatterjee, D., Sinha, A., & Poduval, M. (2019). Musculoskeletal modeling to predict and reduce Antetrior Cruciate Ligament injury during single leg drop jump activity: Synergistic muscle co-activation approach. *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. https://doi.org/10.1109/EMBC.2019.8856321

Nawasreh, Z., Logerstedt, D., Cummer, K., Axe, M., Risberg, M. A., & Snyder-Mackler, L. (2018). Functional performance 6 months after ACL reconstruction can predict return to participation in the same preinjury activity level 12 and 24 months after surgery. *British Journal of Sports Medicine*, *52*(6). https://doi.org/10.1136/bjsports-2016-097095

Nedergaard, N. J., Dalbø, S., Petersen, S. V., Zebis, M. K., & Bencke, J. (2020). Biomechanical and neuromuscular comparison of single- and multi-planar jump tests and a side-cutting maneuver: Implications for ACL injury risk assessment. *Knee*, *27*(2). https://doi.org/10.1016/j.knee.2019.10.022

Palmieri-Smith, R. M., Strickland, M., & Lepley, L. K. (2019). Hamstring muscle activity after primary anterior cruciate ligament reconstruction—A protective mechanism in those who do not sustain a secondary injury? A preliminary study. *Sports Health*, *11*(4), 316–323. https://doi.org/10.1177/1941738119852630

Perry, A., DeFroda, S., Leporace, G., Metsavaht, L., Coxe, C. R., Bierman, A. M., & Chahla, J. (2022). ACL rehabilitation: How can we lessen injury rates? *Operative Techniques in Sports Medicine*, *30*(1), 150892. https://doi.org/10.1016/j.otsm.2022.150892

Pietrosimone, B., Seeley, M. K., Johnston, C., Pfeiffer, S. J., Spang, J. T., & Blackburn, J. T. (2019). Walking ground reaction force post-ACL reconstruction: Analysis of time and symptoms. *Medicine and Science in Sports and Exercise*, *51*(2). https://doi.org/10.1249/MSS.0000000000001776

Piussi, R., Simonson, R., Zsidai, B., Grassi, A., Karlsson, J., Della Villa, F., Samuelsson, K., & Hamrin Senorski, E. (2024). Better safe than sorry? A systematic review with meta-analysis on time to return to sport after ACL reconstruction as a risk factor for second ACL injury. *Journal of Orthopaedic & Sports Physical Therapy*, *54*(3), 161–175. https://doi.org/10.2519/jospt.2023.11977

Rambaud, A. J., Neri, T., Dingenen, B., Parker, D., Servien, E., Gokeler, A., & Edouard, P. (2022). The modifying factors that help improve anterior cruciate ligament reconstruction rehabilitation: A narrative review. *Annals of Physical and Rehabilitation Medicine*, *65*(4), 101601. https://doi.org/10.1016/j.rehab.2021.101601

Ramkumar, P. N., Hadley, M. D., Jones, M. H., & Farrow, L. D. (2018). Hamstring autograft in ACL reconstruction: A 13-year predictive analysis of anthropometric factors and surgeon trends relating to graft size. *Orthopaedic Journal of Sports Medicine*, *6*(6). https://doi.org/10.1177/2325967118779788

Samaan, M. A., Ringleb, S. I., Bawab, S. Y., Greska, E. K., & Weinhandl, J. T. (2018). Altered lower extremity joint mechanics occur during the star excursion balance test and single leg hop after ACL-reconstruction in a collegiate athlete. *Computer Methods in Biomechanics and Biomedical Engineering*, *21*(4). https://doi.org/10.1080/10255842.2018.1452203

San Jose, A. J., Maniar, N., Whiteley, R., Opar, D. A., Timmins, R. G., & Kotsifaki, R. (2023). Lower patellofemoral joint contact force during side-step cutting after return-to-sports clearance following anterior cruciate ligament reconstruction. *The American Journal of Sports Medicine*, *51*(7), 1777–1784. https://doi.org/10.1177/03635465231166104

Shani, R. H., Umpierez, E., Nasert, M., Hiza, E. A., & Xerogeanes, J. (2016). Biomechanical comparison of quadriceps and patellar tendon grafts in anterior cruciate ligament reconstruction. *Arthroscopy: The Journal of Arthroscopic and Related Surgery*, *32*(1). https://doi.org/10.1016/j.arthro.2015.06.051

Sharifi, M., & Shirazi-Adl, A. (2021). Knee flexion angle and muscle activations control the stability of an anterior cruciate ligament deficient joint in gait. *Journal of Biomechanics*, *117*, 110258. https://doi.org/10.1016/j.jbiomech.2021.110258

Shelburne, K. B., Pandy, M. G., Anderson, F. C., & Torry, M. R. (2004). Pattern of anterior cruciate ligament force in normal walking. *Journal of Biomechanics*, *37*(6), 797–805. https://doi.org/10.1016/j.jbiomech.2003.10.010

Shelburne, K. B., Torry, M. R., & Pandy, M. G. (2005). Muscle, ligament, and joint-contact forces at the knee during walking. *Medicine and Science in Sports and Exercise*, *37*(11), 1948–1956. https://doi.org/10.1249/01.mss.0000180404.86078.ff

Shi, D., Zhang, W., Ding, X., & Sun, L. (2020). Parametric generation of three-dimensional gait for robot-assisted rehabilitation. *Biology Open*, *9*(3). https://doi.org/10.1242/bio.047332

Smale, K. B., Alkjaer, T., Flaxman, T. E., Krogsgaard, M. R., Simonsen, E. B., & Benoit, D. L. (2020). Predicting post-operative functional ability from pre-operative measures in ACL-injured individuals. *Scandinavian Journal of Medicine and Science in Sports*, *30*(1). https://doi.org/10.1111/sms.13549

Ueno, R., Navacchia, A., DiCesare, C. A., Ford, K. R., Myer, G. D., Ishida, T., Tohyama, H., & Hewett, T. E. (2020). Knee abduction moment is predicted by lower gluteus medius force and larger vertical and lateral ground reaction forces during drop vertical jump in female athletes. *Journal of Biomechanics*, *103*. https://doi.org/10.1016/j.jbiomech.2020.109669

Wannop, J. W., Worobets, J. T., & Stefanyshyn, D. J. (2012). Normalization of ground reaction forces, joint moments, and free moments in human locomotion. *Journal of Applied Biomechanics*, *28*(6). https://doi.org/10.1123/jab.28.6.665

Webster, K. E., & Feller, J. A. (2019). Clinical tests can be used to screen for second anterior cruciate ligament injury in younger patients who return to sport. *Orthopaedic Journal of Sports Medicine*, *7*(8). https://doi.org/10.1177/2325967119863003

Webster, K. E., & Hewett, T. E. (2019). What is the evidence for and validity of return-to-sport testing after anterior cruciate ligament reconstruction surgery? A systematic review and meta-analysis. *Sports Medicine*, *49*(6), 917–929. https://doi.org/10.1007/s40279-019-01093-x

Wiggins, A. J., Grandhi, R. K., Schneider, D. K., Stanfield, D., Webster, K. E., & Myer, G. D. (2016). Risk of secondary injury in younger athletes after anterior cruciate ligament reconstruction: A systematic review and meta-analysis. *The American Journal of Sports Medicine*, *44*(7), 1861–1876. https://doi.org/10.1177/0363546515621554

Woo, S. L. Y., Hollis, J. M., Adams, D. J., Lyon, R. M., & Takai, S. (1991). Tensile properties of the human femur–anterior cruciate ligament–tibia complex: The effects of specimen age and orientation. *The American Journal of Sports Medicine*, *19*(3), 217–225. https://doi.org/10.1177/036354659101900303

Wu, W., Zeng, W., Ma, L., Yuan, C., & Zhang, Y. (2018). Modeling and classification of gait patterns between anterior cruciate ligament deficient and intact knees based on phase space reconstruction, Euclidean distance and neural networks. *BioMedical Engineering OnLine*, *17*(1), 1–19. https://doi.org/10.1186/s12938-018-0594-1