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Decreased change of direction angle, increased ACL load: angle-dependent anterior cruciate ligament loading across different change of direction sprints in male soccer players

Markus Huthöfer [a,*], Hans Kainz [b], Jana Holder [a], Brian Horsak [c], Gunther Kurz [d], Hermann Schwameder [a]

[a] University of Salzburg, Department of Sport and Exercise Science, Hallein, Austria
[b] Centre for Sport Science and University Sports, University of Vienna, Vienna, Austria
[c] University of Applied Sciences St. Pölten, Center for Digital Health and Social Innovation, St. Pölten, Austria
[d] BioMotion Center, Institute of Sports and Sports Science, Karlsruhe Institute of Technology, Karlsruhe, Germany

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ABSTRACT

Anterior cruciate ligament (ACL) injuries frequently occur during high-speed, non-contact movements such as change of direction (COD) maneuvers. While external joint moments such as the knee abduction moment (KAM) are widely used as surrogate markers of ACL loading, they do not directly quantify tissue loading. Understanding ACL loading at tissue level and how it varies with COD angle may improve prevention and screening protocols. Fifteen recreational male soccer players performed planned 45°, 90°, 135°, and 180° COD sprints. Marker trajectories and ground reaction forces were captured with three-dimensional motion capture system and force plates. Musculoskeletal simulations were conducted in OpenSim using a multi-body knee model and the Concurrent Optimization of Muscle Activations and Kinematics framework. Knee kinematics and kinetics in all three anatomical planes, ACL strain and ACL strain rate were extracted across COD angle conditions. Repeated measures ANOVAs with post-hoc tests were applied. Peak ACL strain ranged from 5.1 to 8.5%, and ACL strain rate reached up to 84%·s^{-1}. Both parameters were highest at 45° COD. These values fall within physiologically plausible ranges reported in in-vitro and in-vivo studies. Despite higher KAMs for increased angles, ACL strain and ACL strain rate decreased with increasing COD angle. Musculoskeletal simulations revealed that smaller COD angles impose greater ACL loading in male soccer players, illustrating that surrogate metrics such as KAM may not accurately reflect ACL loading. These findings emphasize the multifactorial nature of ACL loading. It further demonstrates the value of musculoskeletal modelling as a comprehensive approach to quantify ligament loading and inform angle-specific injury-prevention and testing strategies.

1. Introduction

Anterior cruciate ligament (ACL) injuries are among the most impactful injuries in soccer, with substantial implications for long-term health issues such as early onset of osteoarthritis (Filbay et al., 2022; Webster & Hewett, 2022; Whittaker et al., 2022). The majority of ACL injuries in soccer occur in high-speed, non-contact actions particularly pressing and change of direction (COD) maneuvers (Achenbach et al., 2024; Della Villa et al., 2020; Waldén et al., 2015). In such injury scenarios, ACL loading, whether expressed as force, stress, strain, or strain rate, must have exceeded ligament tolerance.

Numerous studies have examined diverse biomechanical variables during CODs, such as kinematics, external joint moments, and muscle activation, to identify biomechanical determinants of elevated ACL loading (Bencke et al., 2018; Donelon et al., 2020; Dos'Santos et al., 2021; Maniar et al., 2022; Zebis et al., 2009). In this context, the knee abduction moment (KAM) is among the most frequently reported outcome measures, widely interpreted as a surrogate measure for ACL loading (Donelon et al., 2020; Müller-Kühnle et al., 2025). Across studies, KAM has been found to be the lowest for 45° CODs, e.g., 45 vs.

* Corresponding author at: Schlossallee 49, 5400 Hallein, Austria.
E-mail addresses: markus.huthoefer@plus.ac.at (M. Huthöfer), hans.kainz@univie.ac.at (H. Kainz), jana.holder@plus.ac.at (J. Holder), brian.horsak@ustp.at (B. Horsak), gunther.kurz@kit.edu (G. Kurz), hermann.schwameder@plus.ac.at (H. Schwameder).

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110° (Sigward et al., 2015), 45° vs. 90° (Havens & Sigward, 2015) and 45° vs. 90°, 135° and 180° (Schreurs et al., 2017). Therefore, it has been hypothesized that increased COD angles place the knee more at risk (Schreurs et al., 2017).

These findings have reinforced the concept that the biomechanical demands of CODs are angle-dependent (Dos'Santos et al., 2021). However, ACL loading cannot be directly inferred from external surrogates, e.g., KAM. ACL loading emerges from the coupled effects and complex interactions of kinematics, kinetics, and muscle forces (Beaulieu et al., 2023; Nasseri et al., 2021). Consequently, computational approaches that integrate kinematics, kinetics and muscle forces are needed to investigate ACL loading during dynamic tasks where direct in-vivo measurements are not feasible (Nasseri et al., 2020). Musculoskeletal modeling studies that have quantified ACL loading during COD tasks are scarce. In ACL-reconstructed athletes, modeling analyses of cutting have identified side-to-side differences in ACL force (Kotsifaki et al., 2022). It has also been shown that ACL forces increase with higher sprinting velocity at 45° COD (Moon et al., 2023). On tissue level, ACL force leads to ligament strain, which is a key determinant of failure. Bates et al. (2020) have used a cadaveric impact simulator to progressively increase the impact of landings while directly measuring ACL strain. ACL strain increased progressively with loading magnitude.

Moreover, it has been shown that the ACL loading is sensitive to the strain rate. Therefore, not only the deformation itself but also how quickly deformation develops further modulates the ACL loading and failure likelihood (Lee & Hyman, 2002; Pioletti et al., 1999). Accordingly, peak strain and strain rate provide direct, tissue-level insights into ACL loading and injury risk. Yet, to our knowledge, no study has directly compared ACL strain and ACL strain rate across CODs with different angles using musculoskeletal simulations. Understanding if and how ACL strain and ACL strain rate vary with COD angle may help identify specific ACL loading characteristics and inform more targeted injury-prevention strategies. Moreover, angle-dependent information of ACL loading could influence the choice of COD angle for testing and screening protocols, specifically in cases where only one condition can be tested.

Therefore, we have analyzed ACL strain and ACL strain rate across four COD angles (45°, 90°, 135°, 180°) using a detailed biomechanical knee model and sophisticated simulation framework in amateur soccer players. We hypothesize that (1) larger COD angles produce higher peak ACL strain, and (2) the ACL strain rate differs across the COD angle conditions. Additionally, we have analyzed knee joint angles and joint moments to enable comparisons of our findings with previous studies.

2. Methods

2.1. Participants

Fifteen healthy, recreational male soccer players (23.3 ± 2.2 years; 1.81 ± 0.05 m; 79.8 ± 8.1 kg) exercising and competing 3.2 ± 1.1 times per week with a training age of 16.2 ± 3.9 years volunteered to participate in the study. Only male soccer players were included because the data originated from a larger project comparing COD biomechanics between American football and soccer players, for which no comparable female cohort was available. A sex-homogeneous male sample additionally avoided sex as a potential confounder, given evident sex differences in COD biomechanics (Sigward et al., 2012). A priori power analysis based on large effects for KAM reported by Dos'Santos et al. (2021) indicated a required sample size of 14 participants to detect COD condition effects (GPower; $f = 0.40$, $\alpha = 0.05$; power $= 0.95$; correlation among repeated measures $\rho = 0.62$). All participants provided written informed consent. Prior to data collection, the protocol received ethics approval from the University's Institutional Review Board. Athletes had to have no history of lower-extremity surgery and no lower-extremity injury within the past six months. Participants wore standard indoor sport footwear.

2.2. Change of direction sprint protocol

Participants performed planned COD sprints at 45°, 90°, 135°, and 180° COD angle conditions, changing direction with their left leg. Trial order was randomized. Athletes approached the force plates along a marked runway that was 3.5 m long and 50 cm wide. Then executed the cut with the left foot on the force plate, sprinted through a three-meter long, 50 cm wide taped corridor to the finish line (see Fig. 1). Participants received standardized verbal instructions and encouragement to sprint at maximal speed from start to finish. In addition to the marked runway, all trials were recorded using smartphone cameras in slow-motion mode to visually confirm correct execution of the cutting maneuver and ensure that participants did not run curved trajectories. Three valid trials per condition were collected.

2.3. Data collection and reduction

Marker trajectories were recorded using the Cleveland Clinic Marker Set at 250 Hz with a 10-camera infrared motion capture system (Vicon, Oxford, Oxford Metrics Ltd, UK) synchronized with two force plates sampling at 1000 Hz (AMTI, Watertown, MA, USA). All markers were placed by an expert with over ten years of motion analysis experience. Initial contact and toe-off were defined using vertical ground reaction forces (GRF) thresholds at 50 N. Marker trajectories and GRFs were low-pass filtered using a fourth-order, zero-lag Butterworth filter with cut-off frequencies of 10 Hz (Kristianslund et al., 2012). After instrumentation, participants completed a 3-min treadmill warm-up at 8 km/h. Prior to testing, participants performed familiarization trials of the approach run and change of direction task to ensure consistent, natural step patterns and accurate foot placement on the force plates.

2.4. Musculoskeletal modeling

All modeling was performed in OpenSim (Delp et al., 2007). A generic lower-limb model (Lenhart et al., 2015) was scaled to match each participant's anthropometry using the marker data from a static trial. The model included 44 muscle–tendon actuators spanning the left

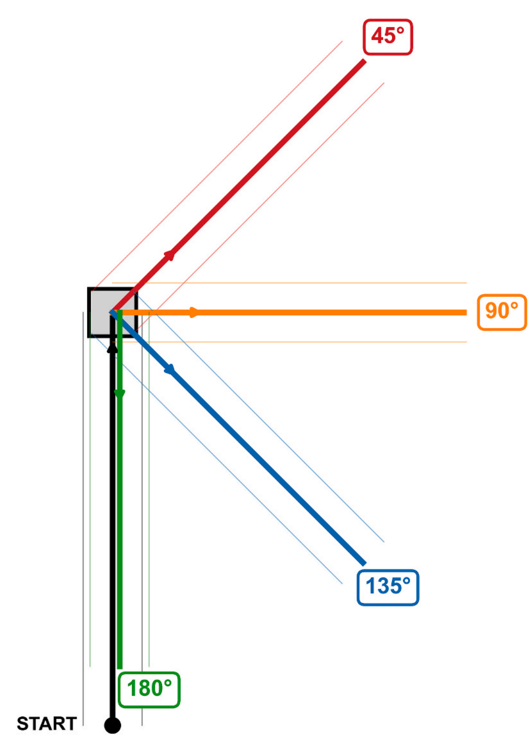

Fig. 1. Change-of-Direction sprint setup.

hip, knee, and ankle joints, 14 ligament bundles (including ACL, posterior cruciate ligament (PCL), medial collateral ligament (MCL), lateral collateral ligament (LCL)) modeled as nonlinear springs, and six-degree of freedom tibiofemoral and patellofemoral joints to permit secondary tibiofemoral motions (ab-/adduction, external/internal rotation, anterior-posterior/medio-lateral/superior-inferior translations) as well as patellofemoral translations and rotations. To represent the muscle strength of our athletes and get physiological-plausible simulation results, maximum isometric muscle forces were multiplied by three and ligament stiffness of ACL, PCL, MCL, and LCL by five. Such adjustments are common in sport-related simulations (Kotsifaki et al., 2022; Pandy et al., 2021; Pürzel et al., 2025). As the original model was based on a female adult (1.65 m, 61 kg) and intended primarily for gait simulations. Therefore, unscaled maximum isometric muscle forces and ligament stiffness values would be insufficient to reproduce the high neuromuscular and mechanical demands of maximal-intensity COD maneuvers. The chosen factors produced peak ACL strain magnitudes within the physiologically plausible range reported by in vitro and in vivo studies (Bates et al., 2020; Luque-Serón & Medina-Porqueres, 2016). As the scaling is generic, findings should be interpreted as relative, condition-dependent differences rather than absolute strain magnitudes.

For the simulation the Concurrent Optimization of Muscle Activations and Kinematics (COMAK) algorithm was used (Brandon et al., 2018; Smith et al., 2016). Inverse kinematics was used to calculate primary joint kinematics based on each participant‘s marker trajectories. The primary kinematics included hip flexion/extension, hip ab-/adduction, hip internal/external rotation, knee flexion/extension, ankle plantar-/dorsiflexion, and ankle subtalar inversion/eversion. Secondary tibiofemoral and patellofemoral kinematics and muscle activations were optimized at each time step to reproduce measured accelerations and static equilibrium in secondary degrees of freedom (Brandon et al., 2018; Smith et al., 2019; Smith et al., 2018). Processing was performed using the autoSIM workflow (Horsak et al., 2025) (https://github.com/fhstp/autoSIM) via MATLAB (R2022b, MathWorks Inc., Natick, MA). The following variables of the left leg were extracted: knee joint angles (°) and external knee joint moments (normalized to body mass (Nm/kg)) in all three anatomical planes, ACL strain (%), and ACL strain rate (%/s).

2.5. Data analysis and statistics

For standardizing task intensity, the trial with the shortest ground contact time (GCT) for each participant and COD condition (45°, 90°, 135°, 180°) was selected for the primary statistical analysis. Within the knee model, each ACL bundle is represented as a nonlinear spring with a pre-defined reference length. ACL strain was computed within the COMAK framework based on the length change of the ACL relative to its original length. Negative strain values therefore indicate bundle lengths below the reference length (i.e., the ligament is in its slack region). As in these cases no tensile forces can be generated, the negative values just indicate the narrowing of the origin and the insertion. ACL strain rate ($\Delta\varepsilon$) was defined as the mean slope of the strain (ε)-time (t)-curve from initial contact (IC) to peak strain:

$$\Delta\varepsilon = \frac{\varepsilon_{peak} - \varepsilon_{IC}}{t_{\varepsilon_{peak}} - t_{\varepsilon_{IC}}}$$

COD condition effects were tested with one-way repeated measures ANOVA. Significant main effects were followed by pairwise comparisons with Bonferroni correction. Furthermore, to assess the robustness of our primary findings, a second repeated measures ANOVA was performed on trial-averaged data. Effect sizes were reported as eta squared ($\eta 2$) with thresholds based on Cohen's guidelines (1988): small (0.010–0.059), medium (0.060–0.149), and large ($\geq$ 0.150). To investigate the influence of GCT on peak ACL strain and ACL strain rate, we additionally conducted a linear mixed model and Pearson correlation analyses within each COD condition on the primary dataset. Statistical significance was defined $p < 0.05$ for all tests. Statistical analyses were conducted in Python (v3.9.21).

3. Results

Peak ACL strain was 8.5 ± 1.5, 6.2 ± 1.3, 5.1 ± 1.4, and 5.4 ± 1.5% for 45°, 90°, 135°, and 180° COD angle, respectively (Figs. 2 and 3). The four COD angle conditions revealed significant differences with large effects for peak ACL strain [$F(3, 42) = 33.4$, $p < 0.001$, $\eta^2 = 0.70$] and ACL strain rate [$F(3, 42) = 27.5$, $p < 0.001$, $\eta^2 = 0.66$]. Post-hoc tests for peak ACL strain showed significant decreases of 2.3%, 3.4%, and 3.1% from 45° to 90°, 135°, and 180° CODs, respectively, and a significant decrease of 1.1% between 90° and 135°. For ACL strain rate, significant differences were observed for 45° vs. 90°, 45° vs. 135°, and 45° vs. 180°, with decreases of 37.0, 41.6, and 34.6%·s^{-1}, respectively, while no differences were found among 90°, 135°, and 180° CODs (Fig. 3).

Significant main effects of COD condition were found for peak knee flexion angle [$F(3,42) = 9.8$, $p < 0.001$, $\eta^2 = 0.41$], peak knee flexion moment [$F(3,42) = 48.1$, $p < 0.001$, $\eta^2 = 0.77$], peak knee abduction angle [$F(3,42) = 20.5$, $p < 0.001$, $\eta^2 = 0.59$], peak knee abduction moment [$F(3,42) = 41.7$, $p < 0.001$, $\eta^2 = 0.75$], peak knee internal rotation angle [$F(3,42) = 15.13$, $p < 0.001$, $\eta^2 = 0.52$], and peak knee internal rotation moment [$F(3,42) = 13.8$, $p < 0.001$, $\eta^2 = 0.50$]. In the sagittal plane, peak knee flexion angles were lowest at 45° COD, with significantly greater flexion observed at 90°, 135°, and 180°. Peak knee flexion moments were highest at 45° COD and decreased compared to 90°, 135°, and 180°. In the frontal plane, both peak knee abduction angles and peak knee abduction moments showed the highest values at 180° compared with all other conditions. Furthermore, peak knee abduction moments were higher at 90° than at 135°, and lowest at 45°. In the transverse plane, peak internal rotation angles and peak internal rotation moments were smallest at 180°. Moreover, peak internal rotation moments were smaller at 90 compared with 135°. To further contextualize ACL loading results, kinematic and kinetic profiles and results are reported in Figs. 4 and 5. Moreover, our secondary robustness analyses on the influence of GCT reproduced the angle-dependent pattern of the primary analysis (see supplementary material).

4. Discussion

The aim of this study was to compare ACL loading between four COD angles (45°, 90°, 135°, 180°) in male amateur soccer players. The primary finding was that both peak ACL strain and ACL strain rate were highest at 45° COD, despite larger KAM for increased COD angles. This highlights the limitations of traditional kinetic surrogates and emphasizes the need of tissue-level metrics for understanding ACL loading mechanisms during CODs.

The present study revealed angle-dependent differences in knee kinematics and kinetics. In the sagittal plane, knee flexion increased with COD angle, consistent with previous findings showing more knee flexion for increased and higher knee flexion moments for decreased COD angles (Dos'Santos et al., 2021).

In the frontal plane, the highest knee abduction angles and moments were observed at 180° and the smallest at 45° COD. Similarly, KAM has previously been found to be lower for 45° vs. 90° (Dos'Santos et al., 2021; Schreurs et al., 2017), for 45° vs. 135° and 180° (Schreurs et al., 2017), and for 45° vs. 110° (Sigward et al., 2015). For the transverse plane, the smallest internal rotation angles and moments were found for 180° COD, whereas Dos'Santos et al. (2021) observed greater peak knee internal rotation moments at 90° compared to 45° and 180° but no differences for 45° to 180°. This discrepancy in secondary kinematics between our findings and previous marker-based studies may arise from methodological differences. Marker-based kinematics are prone to soft-tissue artefacts, which affect transverse kinematics and, via lever arm errors, propagate to derived kinetic parameters (Ancillao et al., 2022; Benoit et al., 2006). The modelling workflow used in our study

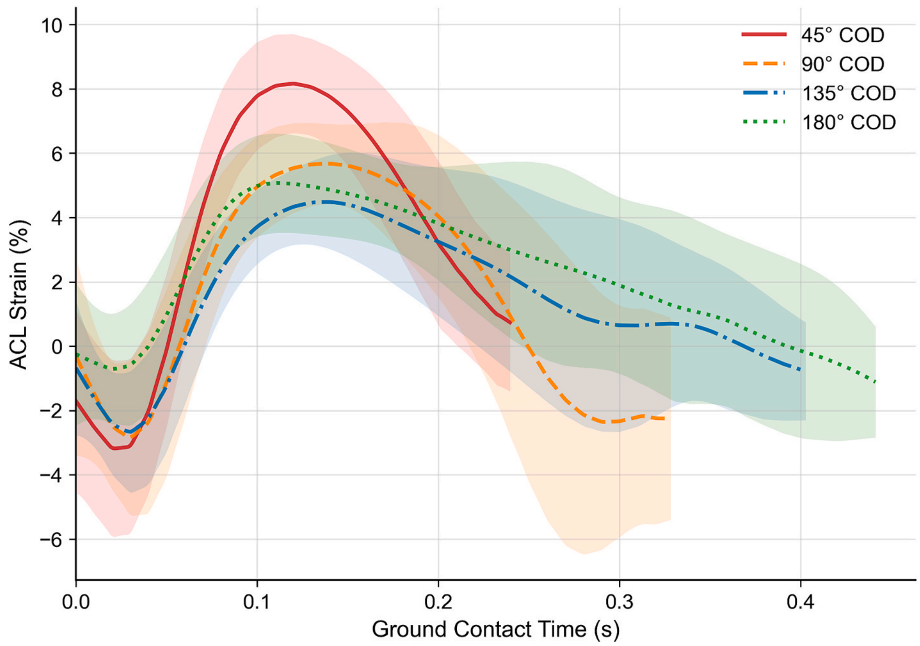

Fig. 2. ACL strain waveforms across different COD conditions (means and standard deviations).

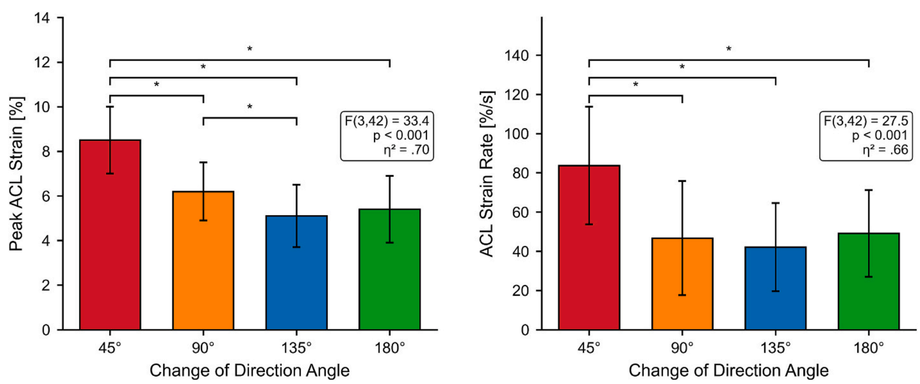

Fig. 3. Peak ACL strain and ACL strain rate across four different change of direction angles. Brackets with "*" indicate significant differences between conditions.

calculates secondary kinematics with an optimization approach and therefore partly overcomes this problem (Brandon et al., 2018; Lenhart et al., 2015; Smith et al., 2018).

Peak ACL strain in our study ranged from 5.1 to 8.5%, slightly higher than the 4.4% reported for in-vivo early-rehabilitation tasks, such as squats and isometric contractions (Luque-Seron & Medina-Porqueres, 2016) but within the range of in-vitro simulated landings (Bates et al., 2020). In the study by Bates et al. (2020), kinetic data from healthy athletes who performed drop vertical jumps in a motion analysis laboratory were used as baseline input for a mechanical impact simulator and cadaveric specimens. In these cadaveric simulated landings the baseline data produced 5.7% peak ACL strain, which increased stepwise with loading magnitude up to 11.6% in pre-failure trials (Bates et al., 2020) Thus, our results fall within physiologically plausible boundaries of ACL strain measured directly in dynamic conditions.

Based on previous findings that larger COD angles are associated with greater KAM, we hypothesized that peak ACL strain would increase with COD angle. Contrary to this hypothesis, ACL strain was highest at 45° COD. KAM has been widely used as a surrogate for ACL loading or risk factor (Donelon et al., 2020; Dos'Santos et al., 2021; Müller-Kühnle et al., 2025; Schreurs et al., 2017), yet across studies and our data, KAM has been consistently lowest at 45°. This finding questions the use of KAM as a direct proxy for ACL loading in CODs.

In line with previous findings, we observed the highest knee flexion moments at 45° CODs (Dos'Santos et al., 2021), which may partly explain one relevant ACL loading pattern. Indeed, Nasseri et al. (2021) demonstrated that the ACL is primarily loaded through sagittal-plane mechanisms. These external moments must be counteracted primarily by the quadriceps, which acts as major antagonist to the ACL by generating anterior shear forces on the tibia, thereby increasing ligament strain. Consequently, a focus solely on frontal or transverse plane kinetics may underestimate ACL loading during CODs. However, it is evident that multiplanar knee loading, such as knee abduction moment, knee internal rotation and anterior tibia shear force, produces the greatest ACL loading (Beaulieu et al., 2023; Markolf et al., 1995).

Beyond kinetics, kinematic findings further contextualize these strain results. We found larger knee flexion angles with increased COD angle, which is in agreement with previous studies (Dos'Santos et al., 2021; Falch et al., 2020; Havens & Sigward, 2015). Importantly, the combination of smaller knee flexion angles and higher flexion moments elevates anterior tibial shear force and, consequently, ACL loading (Beaulieu et al., 2023; Maniar et al., 2022). This provides a biomechanical explanation for our observed peak ACL strains at 45° COD and supports prior video analyses showing that most non-contact ACL injuries occur with relatively small knee flexion (Della Villa et al., 2020; Koga et al., 2010).

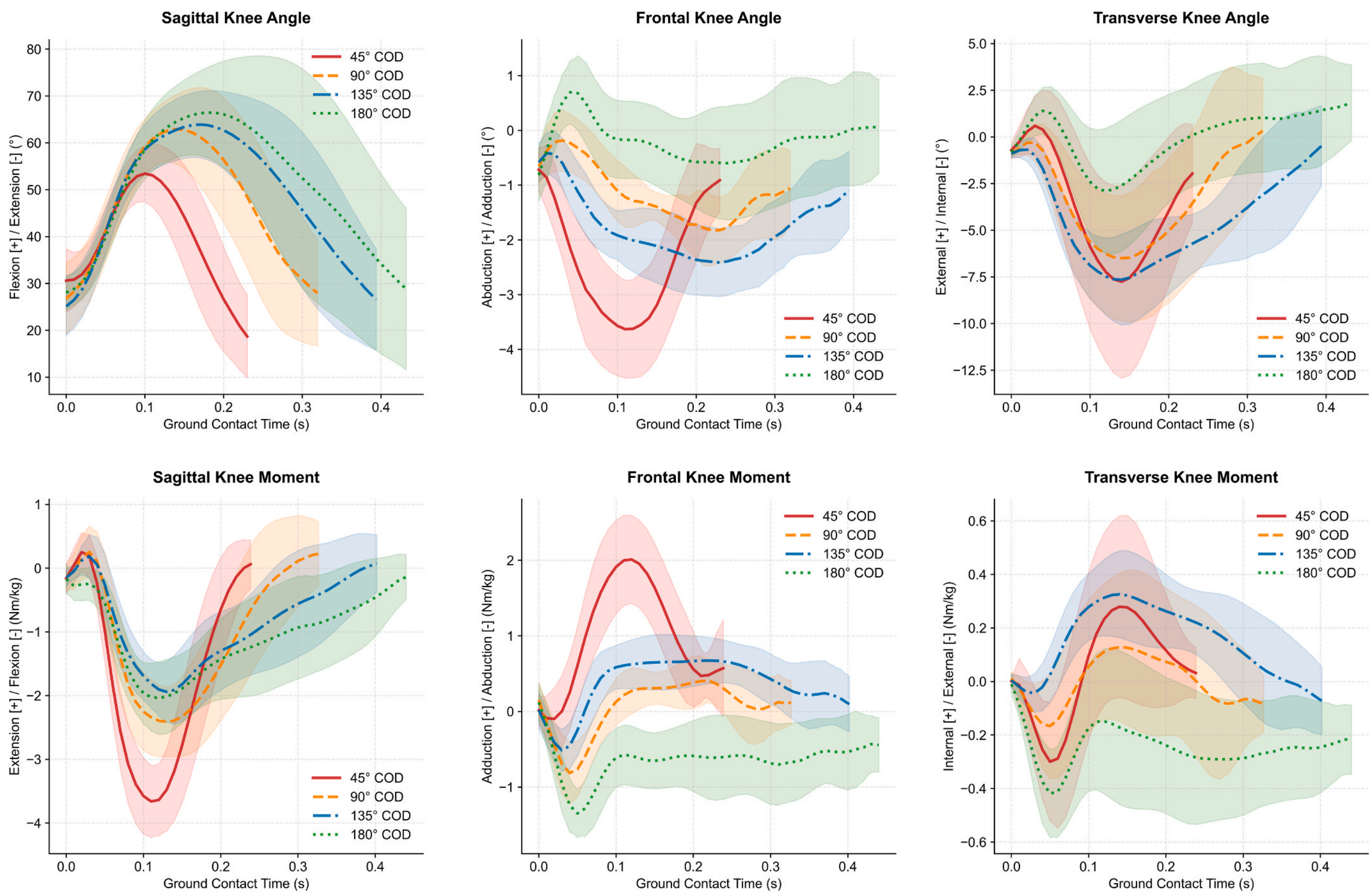

Fig. 4. Knee joint kinematic (top row) and external kinetic (buttom row) waveforms across different change of direction angles.

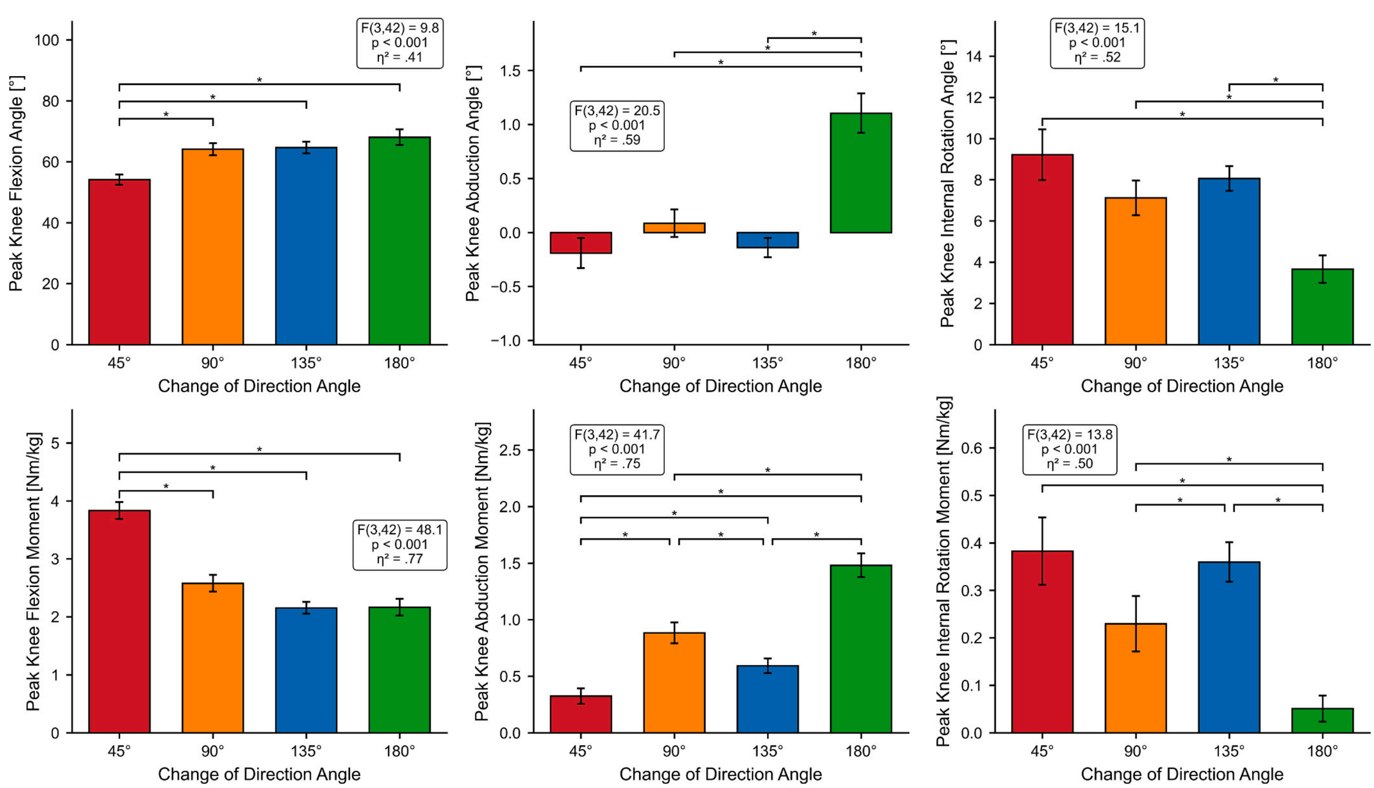

Fig. 5. Peak knee joint kinematics (top row) and external kinetics (buttom row) across different change of direction angles. Brackets with "*" indicate significant differences between conditions.

We hypothesized that ACL strain rate would differ across COD angle conditions, which was confirmed by our results showing the highest values at 45° COD. Since ACL ruptures typically occur shortly after initial contact (Krosshaug et al., 2007) and ligament stress is sensitive to the strain rate (Lee & Hyman, 2002; Pioletti et al., 1999), ACL strain rate represents a relevant parameter of ACL loading.

Animal studies demonstrated that ACL ruptures occur more frequently at higher strain rates (Noyes et al., 1974). Pioletti et al. (1999) showed that at 40%·s^{-1}, 70% of ligament stress was attributable to strain rate, and that at 4% strain, stress at the highest rate was threefold greater than at the lowest. These findings emphasize that both the magnitude and rapidity of deformation, such as peak strain and strain rate, both contribute critically to ligament failure. In our data, ACL strain rate reached up to 84%·s^{-1} at 45° CODs, suggesting that this condition represents the most critical scenario for ACL loading and potential injury risk. This assumption is consistent with epidemiological data showing that 9 of 11 non-contact ACL ruptures in professional soccer occurred during COD maneuvers between 30° and 90°, with only one case each below 30° and above 90° (Waldén et al., 2015). However, our findings should be interpreted as relative, condition-dependent differences rather than as estimates of absolute injury risk. Our primary contribution lies in the pattern of how ACL strain and strain rate change across cutting angles. Regarding the potential influence of GCT, our secondary robustness analyses (trial-averaged ANOVA, linear mixed model and within-condition correlations; see supplementary material) consistently indicated that GCT does not have a relevant effect on ACL loading. Angle-dependent differences are therefore best interpreted as a consequence of the COD angle itself, with GCT representing an inherent mechanical characteristic of the COD task rather than an independent driver.

Several limitations should be acknowledged. First, the musculoskeletal model and COMAK framework were validated for gait simulations. Experimental in-vivo validation for CODs was beyond the scope of this study. However, our simulation results are within the same range as in-vivo and cadaver studies (Bates et al., 2020; Luque-Seron & Medina-Porqueres, 2016), and therefore seem to be physiologically plausible. Second, the optimization procedure choses a muscle coordination strategy toward the cost-function optimum rather than a safety-oriented motor solution, such as protective co-contraction which could affect ACL loading. This limitation is accompanied by the absence of EMG data, which prevented validation of the simulated muscle activations and consideration of subject-specific motor control strategies. Third, the approach distance was limited to the laboratory setup. Therefore, we conducted a subsidiary ANOVA and found significant differences in the approach speed at IC, with the highest values at 45° (4.3 m/s). Since Moon et al. (2023) found no differences between 4 and 5 m/s in ACL force, we assume that the effect of a longer approach distance on ACL loading is rather negligible. Finally, this study included only male recreational soccer players performing planned CODs in laboratory conditions. Therefore, findings may not generalize to female or elite populations, unplanned CODs, or different surfaces.

5. Conclusion

In conclusion, musculoskeletal simulations of COD sprinting showed that 45° CODs imposed the highest ACL strain and ACL strain rate in male soccer players, despite higher KAM for increased angles. These findings suggest that surrogate metrics such as KAM may not adequately reflect ligament loading, emphasizing the need for tissue-level measures in dynamic movements and underscore the multifactorial nature of ACL loading. Our results further suggest that ACL loading during CODs is primarily governed by sagittal plane mechanisms. The combination of lower knee flexion angles and higher flexion moments observed at 45° CODs provides a biomechanical explanation for the increased ligament strain and aligns with video-based evidence indicating that most ACL ruptures occur between 30 and 90° COD angles. The present findings provide insight into COD biomechanics in male soccer players; future studies should determine whether these findings generalize to female athletes.

This study demonstrates the utility of physics-based musculoskeletal simulations to quantify tissue-level ACL loading during dynamic, sport-specific movements. A more detailed understanding of how strain and strain rate vary with COD angle may refine biomechanical screening protocols, inform individualized return-to-sport testing, and guide the development of targeted, evidence-based injury-prevention strategies.

CRediT authorship contribution statement

Markus Huthöfer: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hans Kainz:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Formal analysis, Conceptualization. **Jana Holder:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Brian Horsak:** Writing – review & editing, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Gunther Kurz:** Writing – review & editing, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hermann Schwameder:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2026.113388.

References

Achenbach, L., Bloch, H., Klein, C., Damm, T., Obinger, M., Rudert, M., Krutsch, W., Szymski, D., 2024. Four distinct patterns of anterior cruciate ligament injury in women's professional football (soccer): a systematic video analysis of 37 match injuries. Br. J. Sports Med. 58 (13), 709–716. https://bjsm.bmj.com/content/bjsports/58/13/709.full.pdf.

Ancillao, A., Aertbeliën, E., De Schutter, J., 2022. Effect of the soft tissue artifact on marker measurements and on the calculation of the helical axis of the knee during a squat movement: a study on the CAMS-Knee dataset. Med. Eng. Phys. 110, 103915. https://doi.org/10.1016/j.medengphy.2022.103915.

Bates, N.A., Schilaty, N.D., Ueno, R., Hewett, T.E., 2020. Timing of strain response of the ACL and MCL relative to impulse delivery during simulated landings leading up to ACL failure. J. Appl. Biomech. 36 (3), 148–155.

Beaulieu, M.L., Ashton-Miller, J.A., Wojtys, E.M., 2023. Loading mechanisms of the anterior cruciate ligament. Sports Biomech. 22 (1), 1–29. https://doi.org/10.1080/14763141.2021.1916578.

Bencke, J., Aagaard, P., Zebis, M.K., 2018. Muscle activation during ACL injury risk movements in young female athletes: a narrative review. Front. Physiol. 9, 445. https://pmc.ncbi.nlm.nih.gov/articles/PMC5962681/.

Benoit, D.L., Ramsey, D.K., Lamontagne, M., Xu, L., Wretenberg, P., Renström, P., 2006. Effect of skin movement artifact on knee kinematics during gait and cutting motions measured in vivo. Gait Posture 24 (2), 152–164.

Brandon, S.C., Smith, C.R., Thelen, D.G., 2018. Simulation of soft tissue loading from observed movement dynamics. In: Handbook of human motion. Springer, pp. 395–428.

Della Villa, F., Buckthorpe, M., Grassi, A., Nabiuzzi, A., Tosarelli, F., Zaffagnini, S., Della Villa, S., 2020. Systematic video analysis of ACL injuries in professional male football (soccer): injury mechanisms, situational patterns and biomechanics study on 134 consecutive cases. Br. J. Sports Med. 54 (23), 1423–1432. https://bjsm.bmj.com/content/bjsports/54/23/1423.full.pdf.

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. I.E.E.E. Trans. Biomed. Eng. 54 (11), 1940–1950. https://ieeexplore.ieee.org/stampPDF/getPDF.jsp?tp=&arnumber=4352056&ref=.

Donelon, T.A., Dos'Santos, T., Pitchers, G., Brown, M., Jones, P.A., 2020. Biomechanical determinants of knee joint loads associated with increased anterior cruciate ligament loading during cutting: a systematic review and technical framework. Sports Med. - Open 6 (1), 53. https://doi.org/10.1186/s40798-020-00276-5.

Dos'Santos, T., Thomas, C., Jones, P.A., 2021. The effect of angle on change of direction biomechanics: Comparison and inter-task relationships. J. Sports Sci. 39 (22), 2618–2631. https://doi.org/10.1080/02640414.2021.1948258.

Falch, H.N., Rædergård, H.G., van den Tillaar, R., 2020. Effect of approach distance and change of direction angles upon step and joint kinematics, peak muscle activation, and change of direction performance [original research]. Front. Sports Active Living 2. https://doi.org/10.3389/fspor.2020.594567.

Filbay, S.R., Skou, S.T., Bullock, G.S., Le, C.Y., Räisänen, A.M., Toomey, C., Ezzat, A.M., Hayden, A., Culvenor, A.G., Whittaker, J.L., 2022. Long-term quality of life, work limitation, physical activity, economic cost and disease burden following ACL and meniscal injury: a systematic review and meta-analysis for the OPTIKNEE consensus. Br. J. Sports Med. 56 (24), 1465–1474. https://bjsm.bmj.com/content/bjsports/56/24/1465.full.pdf.

Havens, K.L., Sigward, S.M., 2015. Joint and segmental mechanics differ between cutting maneuvers in skilled athletes. Gait Posture 41 (1), 33–38.

Horsak, B., Krondorfer, P., Unglaube, F., Slijepčević, D., Kranzl, A., 2025. Feasibility of fully automated and semi-personalized musculoskeletal simulations to process large-scale gait datasets. Gait Posture 117, S18–S19. https://doi.org/10.1016/j.gaitpost.2025.01.059.

Koga, H., Nakamae, A., Shima, Y., Iwasa, J., Myklebust, G., Engebretsen, L., Bahr, R., Krosshaug, T., 2010. Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. Am. J. Sports Med. 38 (11), 2218–2225.

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. Orthop. J. Sports Med. 10 (4), 23259671221084742. https://journals.sagepub.com/doi/pdf/10.1177/23259671221084742?download=true.

Kristianslund, E., Krosshaug, T., van den Bogert, A.J., 2012. Effect of low pass filtering on joint moments from inverse dynamics: Implications for injury prevention. J. Biomech. 45 (4), 666–671. https://doi.org/10.1016/j.jbiomech.2011.12.011.

Krosshaug, T., Nakamae, A., Boden, B.P., Engebretsen, L., Smith, G., Slauterbeck, J.R., Hewett, T.E., Bahr, R., 2007. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. Am. J. Sports Med. 35 (3), 359–367.

Lee, M., Hyman, W., 2002. Modeling of failure mode in knee ligaments depending on the strain rate. BMC Musculoskelet. Disord. 3, 3. https://doi.org/10.1186/1471-2474-3-3.

Lenhart, R.L., Kaiser, J., Smith, C.R., Thelen, D.G., 2015. Prediction and validation of load-dependent behavior of the tibiofemoral and patellofemoral joints during movement. Ann. Biomed. Eng. 43 (11), 2675–2685. https://doi.org/10.1007/s10439-015-1326-3.

Luque-Seron, J.A., Medina-Porqueres, I., 2016. Anterior cruciate ligament strain in vivo: a systematic review. Sports Health 8 (5), 451–455. https://doi.org/10.1177/1941738116658006.

Maniar, N., Cole, M.H., Bryant, A.L., Opar, D.A., 2022. Muscle force contributions to anterior cruciate ligament loading. Sports Med. 52 (8), 1737–1750. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9325827/pdf/40279_2022_Article_1674.pdf.

Markolf, K.L., Burchfield, D.M., Shapiro, M.M., Shepard, M.F., Finerman, G.A., Slauterbeck, J.L., 1995. Combined knee loading states that generate high anterior cruciate ligament forces. J. Orthop. Res. 13 (6), 930–935. https://onlinelibrary.wiley.com/doi/pdfdirect/10.1002/jor.1100130618?download=true.

Moon, J., Koo, D., Kim, S., Panday, S.B., 2023. Effect of sprinting velocity on anterior cruciate ligament and knee load during sidestep cutting. Front. Bioeng. Biotechnol. 11, 1033590. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9941960/pdf/fbioe-11-1033590.pdf.

Müller-Kühnle, J., Bill, K., Thun, P., Mai, P., Bagehorn, T., Kamatsuki, Y., Mausehund, L., Solbakken, S., Singh, M., Petrovic, M., Hildebrandt, S., Volden, S., Carlsen, E., Kersting, U., Mørtvedt, A.I., Eriksrud, O., Pasanen, K., Krosshaug, T., 2025. A novel cutting technique and resistance training intervention to improve movement patterns in youth female handball players. JOSPT Open 3 (4), 473–482. https://doi.org/10.2519/josptopen.2025.0144.

Nasseri, A., Khataee, H., Bryant, A.L., Lloyd, D.G., Saxby, D.J., 2020. Modelling the loading mechanics of anterior cruciate ligament. Computational Methods and Programs in Biomedicine 184, 105098. https://doi.org/10.1016/j.cmpb.2019.105098.

Nasseri, A., Lloyd, D.G., Bryant, A.L., Headrick, J., Sayer, T.A., Saxby, D.J., 2021. Mechanism of anterior cruciate ligament loading during dynamic motor tasks. Medicine and Sci. Sports & Exercise 53 (6), 1235–1244. https://doi.org/10.1249/MSS.0000000000002589.

Noyes, F.R., DeLucas, J.L., Torvik, P.J., 1974. Biomechanics of anterior cruciate ligament failure: an analysis of strain-rate sensitivity and mechanisms of failure in primates. J. Bone & Joint Surgery 56 (2), 236–253.

Pandy, M.G., Lai, A.K., Schache, A.G., Lin, Y.C., 2021. How muscles maximize performance in accelerated sprinting. Scand. J. Med. Sci. Sports 31 (10), 1882–1896.

Pioletti, D.P., Rakotomanana, L.R., Leyvraz, P.F., 1999. Strain rate effect on the mechanical behavior of the anterior cruciate ligament–bone complex. Med. Eng. Phys. 21 (2), 95–100. https://doi.org/10.1016/S1350-4533(99)00028-4.

Pürzel, A., Kaufmann, P., Koller, W., Pöhlmann, L., Baca, A., Kainz, H., 2025. Muscle force dynamics across increasing squat intensity conditions in elite powerlifters. Scand. J. Med. Sci. Sports 35 (5), e70058.

Schreurs, M.J., Benjaminse, A., Lemmink, K.A., 2017. Sharper angle, higher risk? The effect of cutting angle on knee mechanics in invasion sport athletes. J. Biomech. 63, 144–150. https://www.sciencedirect.com/science/article/abs/pii/S0021929017304311?via%3Dihub.

Sigward, S.M., Cesar, G.M., Havens, K.L., 2015. Predictors of frontal plane knee moments during side-step cutting to 45 and 110 degrees in men and women: implications for anterior cruciate ligament injury. Clin. J. Sport Med. 25 (6), 529–534. https://pmc.ncbi.nlm.nih.gov/articles/PMC4387120/.

Sigward, S.M., Pollard, C.D., Havens, K.L., Powers, C.M., 2012. The influence of sex and maturation on knee mechanics during side-step cutting. Med. Sci. Sports Exerc. 44 (8), 1497.

Smith, C.R., Brandon, S.C.E., Thelen, D.G., 2019. Can altered neuromuscular coordination restore soft tissue loading patterns in anterior cruciate ligament and menisci deficient knees during walking? J. Biomech. 82, 124–133. https://doi.org/10.1016/j.jbiomech.2018.10.008.

Smith, C.R., Vignos, M.F., Lenhart, R.L., Kaiser, J., Thelen, D.G., 2016. The influence of component alignment and ligament properties on tibiofemoral contact forces in total knee replacement. J. Biomech. Eng. 138 (2), 021017. https://pmc.ncbi.nlm.nih.gov/articles/PMC4844247/pdf/bio-15-1520_021017.pdf.

Smith, C.R., Won Choi, K., Negrut, D., Thelen, D.G., 2018. Efficient computation of cartilage contact pressures within dynamic simulations of movement. Computer Methods in Biomechanics and Biomedical Engineering: Imaging & Visualization 6 (5), 491–498.

Waldén, M., Krosshaug, T., Bjørneboe, J., Andersen, T.E., Faul, O., Hägglund, M., 2015. Three distinct mechanisms predominate in non-contact anterior cruciate ligament injuries in male professional football players: a systematic video analysis of 39 cases. Br. J. Sports Med. 49 (22), 1452–1460. https://doi.org/10.1136/bjsports-2014-094573.

Webster, K.E., Hewett, T.E., 2022. Anterior cruciate ligament injury and knee osteoarthritis: an umbrella systematic review and meta-analysis. Clin. J. Sport Med. 32 (2), 145–152. https://doi.org/10.1097/jsm.0000000000000894.

Whittaker, J.L., Losciale, J.M., Juhl, C.B., Thorlund, J.B., Lundberg, M., Truong, L.K., Miciak, M., Van Meer, B.L., Culvenor, A.G., Crossley, K.M., 2022. Risk factors for knee osteoarthritis after traumatic knee injury: a systematic review and meta-analysis of randomised controlled trials and cohort studies for the OPTIKNEE Consensus. Br. J. Sports Med. 56 (24), 1406–1421. https://bjsm.bmj.com/content/bjsports/56/24/1406.full.pdf.

Zebis, M.K., Andersen, L.L., Bencke, J., Kjær, M., Aagaard, P., 2009. Identification of athletes at future risk of anterior cruciate ligament ruptures by neuromuscular screening. Am. J. Sports Med. 37 (10), 1967–1973.