BIOMECHANICAL EFFECTS OF A SIX-WEEK CHANGE OF DIRECTION TECHNIQUE MODIFICATION INTERVENTION ON ANTERIOR CRUCIATE LIGAMENT INJURY RISK

ABSTRACT

The aim of this study was to evaluate the biomechanical effects of a six-week change of direction (COD) technique modification intervention on anterior cruciate ligament (ACL) injury risk (i.e., multiplanar knee joint loads) during 45° (CUT45) and 90° (CUT90) side-step cutting. A non-randomized, controlled 6-week intervention study was administrated. 15 male multidirectional sport athletes formed the intervention group (IG) who participated in two 30-minute COD technique modification sessions per week, while 12 male multidirectional sport athletes formed the control group (CG) and continued their normal training. Subjects performed six trials of the CUT45 and CUT90 task whereby pre-to-post intervention changes in lower-limb and trunk kinetics and kinematics were evaluated using three-dimensional motion and ground reaction force analysis. Two-way mixed analysis of variances revealed no significant interaction effects of group for CUT45 and CUT90 multiplanar knee joint loads ($p \geq 0.116$, $\eta^2 \leq 0.096$); however, considerable individual variation was observed (positive (n=5-8) and negative responders (n=7-8)). Based on IG group means, COD technique modification resulted in no meaningful reductions in multiplanar knee joint loads. However, individually, considerable variation was observed, with "higher-risk" subjects generally responding positively, and subjects initially considered "low-risk" tending to increase their multiplanar knee joint loads, albeit to magnitudes not considered hazardous or "high-risk". COD technique modification training is a simple, effective training method, requiring minimal equipment that can reduce knee joint loads and potential ACL injury risk in "higher-risk" subjects without compromising performance.

Keywords: side-step; side-stepping; cutting; knee abduction moment; injury mitigation

INTRODUCTION

Directional changes are a fundamental movement performed in sports, often performed in scenarios such as evading an opponent or moving into space to receive a pass (13). Changing direction, however, is also a key action associated with non-contact anterior cruciate ligament (ACL) injuries in sports such as soccer (6), rugby (35), and American football (25), due to the propensity to generate high multiplanar knee joint loading (flexion, rotation, and abduction loading) during the plant foot contact (7, 8, 29), thus increasing ACL strain (32, 38). ACL injuries are a debilitating injury with short- and long-term consequences (financial, health, and psychological) (21, 31), with an elevated and earlier risk of developing osteoarthritis a primary concern (31). Therefore, training interventions that can mitigate ACL injury risk during COD are of great interest to practitioners working with multidirectional athletes.

Although ACL injury risk factors are multifactorial (anatomical, hormonal, biomechanical, neuromuscular, and environmental) (21), ACL injuries occur when an applied load exceeds the ligaments' tolerance (38); thus, to reduce ACL injury risk, particularly non-contact ACL injury, an effective strategy is to modify an athlete's movement mechanics to reduce the magnitude of knee joint loading through biomechanically and neuromuscular informed training interventions (17, 21). COD techniques with a wide lateral foot plant, greater hip abduction angles, increased internal initial foot progression angles, increased initial hip internal rotation angles, greater initial and peak knee abduction angles, reduced knee flexion angles, greater lateral trunk flexion, greater ground reaction forces (GRF), and greater approach velocities are associated with greater knee abduction moments (KAM) (12, 14, 17) and thus ACL injury risk (22, 32). Additionally, wide lateral foot plant distances, trunk rotation towards the stance limb, trunk flexion displacements, and hip internal rotation moments are associated with greater knee internal rotation moments (KIRM) (8, 17), which when combined with KAMs produces greater ACL strain (multiplanar) compared to uniplanar loading (32, 38). As such, addressing and modifying the aforementioned variables associated with KAMs and KIRMs could be an effective strategy for reducing ACL loading and thus potential ACL injury risk during COD (15, 17).

As highlighted in a recent scoping review (15), COD technique modification training is a potentially effective training strategy for reducing “high-risk” COD mechanics and subsequent knee joint loads (1, 4, 7, 26). Reducing knee joint loads can be achieved via reducing the magnitude of the moment arm, GRF, or a combination of the two (29). Decreases in frontal and transverse knee joint loads during cutting have been demonstrated following acute (8) and chronic (7) COD technique modification via alterations in lateral foot plant distance and orientation, and trunk alignment. Additionally, increasing knee flexion acutely and modifying lower-limb and trunk postures can reduce cutting peak KAMs (1), while a 6-week COD technique modification intervention which encouraged earlier braking during the penultimate foot contact (PFC), backwards trunk inclination, and a neutral foot posture during 180° turning reduced peak KAMs (26). However, the aforementioned six-week COD technique modification intervention studies did not have a control group (CG); thus, the result should be treated with caution because it is uncertain whether such changes were “real”.

To our best knowledge, only one study has examined the effect of COD technique modification on cutting movement quality which contained a CG (11). Interestingly, six-weeks’ COD speed and technique modification which focused on external cues to encourage greater PFC braking, trunk lean towards the intended direction of travel, and rapid and forceful push-off improved cutting performance and cutting movement assessment scores (movement quality) (11). Although these results are promising, and the cutting movement assessment score has been validated and associated with greater peak KAMs (12), movement quality was examined qualitatively and therefore must be further evaluated using three-dimensional motion and GRF analysis to confirm its efficacy. Therefore, the primary aims of this study were two-fold: 1) to evaluate the effectiveness of a 6-week COD technique modification intervention on COD injury risk multiplanar knee joint loads (KAM, KIRM, knee flexion moment) during 45° (CUT45) and 90° (CUT90) side-step cutting; and 2) to identify which kinetic and kinematic factors explain changes in knee joint loads. Additionally, an individual approach has been recommended when analyzing the effects of injury mitigation training program because inferences based on group means only may conceal potentially meaningful information (3, 18). Therefore, a secondary aim was to examine the individual responses (positive / negative) following COD technique modification training. The findings of this research may assist in the development of more effective field-based ACL injury mitigation programs. It was hypothesized that a COD technique modification program would reduce knee joint loads in multidirectional athletes, and that changes in technique variables initial foot progression angle, lateral trunk flexion, knee flexion angle at initial contact, and PFC horizontal braking force will explain reductions in knee joint loads.

METHODS

Experimental approach to the problem

A non-randomized, controlled 6-week intervention study with a repeated measures pre-to-post test design was used (Figure 1). Male multidirectional sport athletes were recruited for the intervention group (IG) and completed a 6-week COD technique modification training program (Supplementary material 1). Conversely, male multidirectional sport athletes acted as the CG. Pre-to-post assessments of CUT45 and CUT90 biomechanics were assessed using three-dimensional motion and GRF analysis to monitor the training intervention's effectiveness. This was performed at the same time of day for each subject to control for circadian rhythm.

*** Insert Figure 1 about here***

Subjects

30 men from multidirectional sports (amateur/semi-professional) participated in this study. Based on previous work for pre-to-post (dependent t-test) peak KAMs changes during 180° turning (26), a minimum sample size of 14 per group was determined from an *a priori* power analysis using G*Power (Version 3.1, University of Dusseldorf, Germany) (16). This was based upon an effect size of 0.73, power of 0.80, and type 1 error of 0.05.

Sixteen males (soccer n=12, rugby n=4; age: 23.5±5.2 years; height: 1.80±0.05m; mass: 81.6±11.4 kg) were recruited for the IG. Conversely, fourteen men (soccer n=9, rugby n=4, field hockey n=1; age: 22.2±5.0 years; height: 1.76±0.08 m; mass: 72.7±12.4 kg) acted as the CG and continued their normal sport and resistance training sessions. Non-significant small to moderate differences in age, height, and mass were observed (p = 0.066-0.496, g = 0.268-0.746). The investigation was approved by the Institutional Ethics Review Board (HSR1617-131), and all subjects were informed of the benefits and risks of the investigation prior to signing an institutionally approved consent form to participate in the study. All subjects from both groups had ≥5 years training experience in their respective sport and had never sustained a severe knee injury prior to testing. All subjects had minimum one years' resistance training experience, all performed two 60-minute resistance training sessions a week, and were all in a strength mesocycle. At the time of the training intervention, all subjects completed two 90-minute skills sessions and played one competitive match a week. All procedures were carried out during the competitive season to ensure that no large physical changes were made because of the conditioning state. To be included in the study and used for further analysis, subjects were not allowed to miss more than two of the 12 sessions in total (i.e., ≥83% compliance rate). Subsequently, due to match-related injuries or illness, one and two subjects withdrew from the IG and CG, resulting in sample sizes of 15 and 12 (Figure 1), respectively. IG subjects completed on average 11.9±0.4 sessions (98.3±3.5%), with 12 subjects completing 12 (100%) sessions and three completing 11 sessions (91.7%).

Procedures

The warm up, cut, marker placement, and three-dimensional motion analysis procedures were based on previously published methodologies (10, 27, 33). Briefly, each subject performed six trials of the 45° and 90° (5-m entry and 3-m exit) side-step cut (right limb push-off) as fast as possible and were provided with standardized footwear to control for shoe-surface interface (Balance W490, New Balance, Boston, MA, USA). Marker and force data were collected over the PFC and final foot contact (FFC) using ten Qualisys Oqus 7 (Gothenburg, Sweden) infrared cameras (240 Hz) operating through Qualisys Track Manager software (Qualisys, version 2.16 (Build 3520), Gothenburg, Sweden) and GRFs were collected from two 600 mm × 900 mm AMTI (Advanced Mechanical Technology, Inc, Watertown, MA, USA) force platforms (Model number: 600900) embedded into the running track sampling at 1200 Hz, respectively. Using the pipeline function in visual three-dimensional, joint coordinate (marker) and force data were smoothed using a Butterworth low-pass digital filter with cut-off frequencies of 15 and 25 Hz, respectively. The kinematic model process was based on previous reported methodologies (10, 27, 33). Lower limb joint moments were calculated using an inverse dynamics approach (42) through Visual three-dimensional software (C-motion, version 6.01.12, Germantown, USA) and were defined as external moments, normalized to body mass. Joint kinematics and GRFs were also calculated using Visual three-dimensional, while GRF braking characteristics were normalized to body weight, with vertical, anterior-posterior, and medio-lateral corresponding to Fz, Fx, and Fy, respectively. Horizontal centre of mass velocity at FFC touch-down was calculated as described previously (27).

Primary and secondary outcome measures: cutting kinetic and kinematic variables

Supplementary material 2 provides a full description the variables examined, definitions, and calculations. The following kinetic and kinematics were examined during the FFC for both tasks: peak KAM, KIRM, and knee flexion moments, and peak and initial knee abduction angles. These were considered the primary injury risk outcome variables and calculated over weight acceptance (initial contact to maximum knee flexion). Additionally, the following technical and mechanical variables associated with greater knee joint loads were also investigated for both tasks (12, 17): peak vertical braking force, velocity at FFC, lateral trunk flexion angle, initial foot progression angle, lateral foot plant distance, peak and initial hip rotation angle, and knee flexion angle (peak, initial, range of motion). Additionally, PFC mean horizontal braking force was examined during the PFC for CUT90 only. Five trials were used in the analysis for each subject, and the average of individual trial peaks for each variable were calculated (10). A subset of the sample (*n*=10) performed the cuts on two separate occasions separated by 7 days to establish between-session reliability with the data considered high (intraclass correlation coefficient = 0.704-0.928, coefficient of variation = 5.3-14.8%).

<u>6-week COD technique modification training intervention</u>

A six-week COD technique modification intervention described in Supplementary material 1, was performed by the IG twice a week (30 minutes per session, ≥48 hours between sessions). The intervention was adapted from a previously successful six-week COD speed and technique modification training intervention (11), which focused on pre-planned low intensity decelerations, cuts, and turns (weeks 1-2), before progressing intensity via velocity and angle (weeks 3-4), and introducing a stimulus with increased intensity (weeks 3-6). The duration, distances, and number of CODs were similar to previous research (11, 26). The sessions were led by the principle researcher who is a certified strength and conditioning specialist, and took place in the Human Performance Laboratory using the same surface used for testing. Athlete-to-coach ratios ranged from 5-8:1.The technique modification focused on three aspects based on the success of a previous COD speed and technique modification intervention and training recommendations (11, 13, 26): 1) "slam on the brakes" (to reduce cutting limb GRF (for the 90° task only)); 2) "cushion and push/punch the ground away" (to reduce knee abduction angles and encourage active limb at touch-down); and 3) "face towards the direction of travel" (to reduce lateral trunk flexion and trunk rotation over stance limb). Subjects were given individual feedback regarding their technique, and external verbal coaching cues were used to facilitate better motor skill retention (11, 13).

Statistical Analyses

All statistical analyses were performed using SPSS v25 (SPSS Inc., Chicago, IL, USA) and Microsoft Excel (version 2016, Microsoft Corp., Redmond, WA, USA). Normality was inspected for all variables using a Shapiro-Wilks test. A two-way mixed analysis of variance (ANOVA) (group; time) with group as a between-participants factor measured at 2 levels (IG and CG), and time (pre- and post-training measures) the within-subject factor. This was used to identify any significant interaction (group × time) effects for outcome variables between IG and CG, pre-to-post testing. A Bonferroni-corrected pairwise comparison design was used to further analyze the effect of the group when a significant interaction effect was observed. Partial eta squared effect sizes were calculated for all ANOVAs with the values of 0.010-0.059, 0.060-0.149, and ≥0.150 considered as small, medium, and large (2), respectively.

Pre-to-post changes in variables for each group were assessed using paired sample t-tests (parametric) and Wilcoxon-sign ranked tests (non-parametric). Magnitudes of differences were assessed using Hedges' *g* effect sizes with 95% confidence intervals, and interpreted as trivial (≤0.19), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), very large (2.00–3.99), and extremely large (≥4.00) (24). Group mean changes were also calculated and interpreted as ratios relative to the smallest worthwhile change (SWC). The SWC was calculated as 0.2 × between-subject SD. Comparisons in post-intervention primary outcome variables and changes in outcome variables between the IG and CG were also assessed using independent sample t-tests or Mann-Whitney U tests, with effect sizes as outlined above. Furthermore, to link changes in knee joint loads with cutting kinetic and kinematic changes, Pearson's correlations (parametric) or Spearman's correlations (non-parametric) were calculated with 95% confidence intervals, and p values Bonferroni corrected to control for type 1 error. Correlations were interpreted as trivial (0.00-0.09), small (0.10–0.29), moderate (0.30–0.49), large (0.50–0.69), very large (0.70–0.89), nearly perfect (0.90–0.99), and perfect (1.00) (23). A correlation cut-off value of ≥0.40 was considered relevant (41). Statistical significance was defined as $p \leq 0.05$ for all tests. Finally, similar to previous work (34), individual analyses were performed to quantify for each variable and each group the number of positive, negative, and non-responders. For all variables of interest, positive or negative responses were considered as an individual change ≥SWC, while trivial responses (non-responder) was considered ≤SWC.

RESULTS

The two-way mixed ANOVAs results are presented in Table 1, and pre-to-post changes in cutting biomechanics are presented in Tables 2-3.

Insert Table 1 here

A medium, non-significant interaction effect for CUT45 peak KAM was observed (Table 1), with the CG showing significantly greater peak KAMs (p=0.013, g=-1.00) post-intervention compared to the IG. Small and non-significant increases in IG CUT45 peak KAMs and KIRMs were observed (Table 2, Figure 2a,b) post-intervention. Large individual variation for IG changes in peak KAMs and KIRMs were observed, with five positive and eight negative responders (Figures 2a,b). Trivial to moderate differences in age (23.8 ± 2.7 vs 23.6 ± 7.0 years, p = 0.959, g = 0.03), height (1.78 ± 0.05 vs. 1.82 ± 0.05 m, p = 0.266, g = -0.74), and mass (80.5 ± 5.2 vs 84.0 ± 13.8 kg, p = 0.606, g = -0.31) were observed between positive and negative responders for CUT45 KAMs and KIRMs. Importantly, large, significant increase in CG peak KAMs post-intervention (Table 2, Figure 2a) were demonstrated but differences in KIRMs were non-significant and trivial (Table 2, Figure 2b).

No significant interaction effect for knee flexion moments were observed, and peak knee flexion moment changes were non-significant and trivial and small for the IG and CG (Table 1-2, Figure 2c), respectively. Initial and peak knee abduction angles significantly increased for both groups (Table 2). Medium to large significant interaction effects were observed for peak knee flexion angle and range of motion, and FFC velocity (Table 1). IG subjects produced small to moderately significantly greater initial foot progression angles, greater initial hip external rotation, greater FFC velocities, and smaller knee flexion angle range of motion post-intervention (Table 2). CG subjects demonstrated significantly greater initial foot progression angles post-intervention only (Table 2). No other significant changes in IG or CG cutting mechanics were observed post-intervention, including peak vertical braking force, lateral trunk flexion angle, and lateral foot plant distance; however, considerable variation in positive and negative responders were observed (Table 2).

Insert Table 2 here

Insert Figure 2 here

No significant interaction effects were observed for CUT90 injury risk variables (Table 1). IG changes in peak KAMs were non-significant and trivial (Table 3, Figure 3a) post-intervention. Large individual variation in IG peak KAMs changes were observed, with eight positive and seven negative responders (Table 3, Figure 3a). The CG demonstrated a small, non-significant increase in peak KAMs post-intervention (Table 3, Figure 3a). A small, non-significant increase in IG peak KIRM was observed (Table 3, Figure 3b) post-intervention. Large individual variation in IG peak KIRMs changes were observed, with eight positive and seven negative responders (Table 3, Figure 3b). A small, non-significant reduction in peak KIRMs were observed for the CG post-intervention (Table 3, Figure 3b). Trivial to moderate differences in age (23.1 ± 4.7 vs 24.0 ± 6.0 years, $p = 0.757$, $g = -0.15$), height (1.81 ± 0.05 vs. 1.79 ± 0.06 m, $p = 0.0468$, $g = 0.36$), and mass (78.2 ± 10.4 vs 85.4 ± 12.0 kg, $p = 0.229$, $g = -0.61$) were observed between positive and negative responders for CUT90 KAMs and KIRMs.

No knee flexion moment significant interaction effect was observed, and changes were non-significant and trivial for the IG and CG (Tables 1 & 3, Figure 3c). Initial and peak knee abduction angles moderately significantly increased post-intervention for both groups (Table 3). Large significant interaction effects were observed for initial foot progression angle and knee flexion angle range of motion (Table 1). IG subjects produced small to moderately significantly greater PFC mean horizontal braking forces, greater initial foot progression angles, greater initial knee flexion angles, and smaller knee flexion angle range of motion (Table 3). No other significant changes in IG or CG cutting mechanics were observed post-intervention, including peak vertical braking force, lateral trunk flexion angle, lateral foot plant distance, and FFC velocity; however, considerable variation in positive and negative responders were observed (Table 3).

Insert Table 3 here

Insert Figure 3 here

Decreases in CUT45 peak KAM were very largely associated with decreased peak knee abduction angles; largely associated with decreased initial foot progression angle and peak knee flexion moment; and moderately associated with decreased initial knee abduction angle and KIRM (Table 4). Additionally, CUT45 peak KIRM decreases were moderately associated with decreased peak KAM, decreased knee flexion moment, and decreased lateral trunk flexion (Table 4). Decreases in CUT90 peak KAM were moderately associated with increased PFC mean horizontal braking force, decreased knee flexion moment, and decreased FFC velocity (Table 4). Furthermore, CUT90 peak KIRM decreases were moderately associated with decreased peak and initial knee abduction angle, decreased lateral foot plant distance, and decreased peak vertical braking force (Table 4).

Insert Table 4 here

DISCUSSION

The primary aims of this study were two-fold: 1) to examine the biomechanical effects of a COD technique modification intervention on multiplanar knee joint loads associated with increased ACL loading; and 2) to identify which kinetic and kinematic factors explain changes in knee joint loads. Based on group means, a 6-week COD technique modification intervention resulted in no meaningful changes in multiplanar knee joint loads post-intervention (Tables 1-3, Figures 2-3), refuting the study hypotheses. However, a secondary aim of the intervention study was to examine the individual responses, and considerable individual variation (i.e., positive and negative responders) and mixed responses following the intervention for multiplanar knee joint loads and mechanical and technical associate variables were observed (Tables 2-3, Figures 2-3). Generally, subjects who displayed initially (pre-intervention) high multiplanar knee joint loads and thus considered potentially "high-risk", responded positively and demonstrated reductions (Figures 2-3). Conversely, subjects initially considered "low-risk" tended to increase their multiplanar knee joint loads, albeit to magnitudes not considered hazardous or "high-risk". Consequently, COD technique modification is a simple, effective training method for reducing knee joint loads in "higher-risk" subjects without compromising performance.

A key strategy to reduce potential non-contact ACL injury risk is reducing multiplanar knee loads which strain the ACL (7, 17, 21, 30). COD technique modification is one training strategy that can acutely reduce knee joint loads during cutting (1, 4, 8), while reductions in peak KAMs have also been observed following 6-weeks technique modification during COD (7, 26). In the present study, no significant interaction effects were observed for any knee joint loads (Table 1), and pre-to-post changes in multiplanar knee joint loads for the IG were non-significant with trivial to small effect sizes (Tables 2-3, Figures 2-3). These results contrast to previous work (7, 26); however, notably, the IG increased their FFC velocity which can amplify knee joint loads (14). Additionally, these two previously successful interventions did not contain a CG (7, 26). The present study contained a CG which notably demonstrated a large increase in CUT45 peak KAMs, and a non-significant yet small increase in CUT90 peak KAMs post-intervention (Tables 2-3, Figures 2-3). Although difficult to fully explain this finding, Staynor et al. (40) also reported increased KAMs and KIRMs for a CG post-intervention (ES = 0.36-0.56), which was potentially attributed to the lack of specific injury mitigation training performed in-season. Thus, the lack of specific COD training with corrective feedback for the CG may partially explain the increased peak KAMs post-intervention in the present study.

Dempsey et al. (7) is the only other study to investigate the effects of side-step technique modification training on knee joint loads and found 6-weeks training produced significant reductions in peak KAMs, attributed to positive changes in lateral trunk flexion and lateral foot plant distance. It is worth noting, however, that peak KIRMs remained unchanged (7). The findings contrast to the present study that observed no meaningful reductions in IG multiplanar knee joint loads (Tables 1-3). However, this discrepancy could be attributed to differences in the training intervention and methodology. Dempsey et al. (7) had lower athlete-to-coach ratios of 1-2:1 and also used video feedback to provide biofeedback regarding technique. Harris et al. (19) has also demonstrated that technique video feedback improved cutting movement quality in three female soccer players. Conversely, the present study contained higher athlete-to-coach ratios (~5:1) and provided no video feedback, which may partially explain why no meaningful reductions in IG knee joint loads, based on group means, were observed. Indeed, it does appear that COD technique modification with biofeedback is an effective strategy which practitioners could implement in the field with small athlete-to-coach ratios. However, in "real-world" environments, practitioners may not have the time and resources to apply biofeedback, particularly with large work athlete-to-coach ratios, as highlighted by previous research (9).

An integral difference between the two studies were the targeted technical modifications, with Dempsey et al. (7) instructing an upright trunk posture in the frontal plane and reducing lateral foot plant distance with the use of line markings for acceptable foot placement. While the present study did aim to alter frontal plane trunk control, subjects were instructed to "cushion and push the ground way", while not restricting lateral foot plant distance because of the potential detrimental effects narrowing may have on medio-lateral impulse and subsequent performance (13, 20). The present study attempted to increase initial knee flexion angles, improve frontal plane knee control, and encourage PFC dominant braking strategies (for CUT90 only) because these are techniques that could reduce knee joint loads without negatively impacting performance (13, 17). Finally, Dempsey et al. (7) performed the side-steps at a controlled approach velocity, whereas CODs were performed as fast as possible in the present study, to increase ecological validity and improve athlete and coach adherence to the training intervention (17, 20). Crucially, IG subjects moderately increased their FFC velocity during CUT45 which may increase knee joint loads (14, 33), whereas CUT90 changes were trivial effect. Consequently, this finding may partially explain the lower number of CUT45 positive (5 vs. 8) responders following he intervention compared to CUT90.

Based on group means, no meaningful changes in IG multiplanar knee joint loads were observed post-intervention (Tables 1-3). In applied and clinical settings, however, practitioners do not work with group means but individuals. Figures 2-3 and Tables 2-3 illustrate the IG multiplanar knee joint loads individual responses following the training intervention, showing considerable individual variation (i.e., positive and negative responders). This observation corroborates previous research that has shown individual variation following injury mitigation training (3, 5, 18, 36). Generally, subjects with initially high multiplanar knee joint loads, and thus considered to be potentially at higher injury risk (21, 22), responded positively and demonstrated reductions (Figures 2-3). This observation is similar to previous research that found "higher-risk" female athletes responded favourably to injury mitigation training by displaying greater reductions in landing KAMs compared to "lower-risk" athletes (5, 18, 36). The present study is the first to have examined the individual changes in knee joint loads following COD technique modification, highlighting that an individual approach is needed because inferences based on group means only may conceal potentially meaningful information (3, 18).

Changes in postures and mechanics associated with increased knee joint loads were also assessed in the present study. Contrary to previous research (7), no meaningful changes in lateral foot plant distance or lateral trunk flexion were observed following COD technique modification training (Tables 1-3). The finding that lateral foot plant distance did not change, based on group means, is unsurprising because this was not a specific targeted technical change. Conversely, it is surprising that lateral trunk flexion angles did not meaningfully reduced because subjects were specifically given the verbal cue to "lean and face towards the intended direction of travel". For example, Staynor et al. (40) observed lateral trunk flexion angles reductions following mixed training (body weight plyometric, resistance, and balance exercises), while King et al. (28) found a three-phase program (intersegmental control and strength, intersegmental control during running and COD) reduced lateral trunk flexion angles during cutting. Potentially, verbal cueing does not provide a sufficient stimulus to evoke frontal plane trunk control changes and thus, increases in physical capacity and intersegmental control is needed through direct conditioning (28, 40). However, individual responses revealed eight and seven subjects positively reduced their lateral trunk flexion angles for CUT45 and CUT90 (Tables 2-3), respectively. As such, the mixed responses to the training intervention conceals potentially meaningful differences based on group mean analysis, and highlights that an individual approach is needed when monitoring changes in COD biomechanics (3, 18).

Cutting postures with limited knee flexion and high impact GRFs "high-risk" characteristics of non-contact ACL injury (25, 35) and associated with increased knee joint loads (32, 38). Although no meaningful reduction in peak vertical braking force was observed, a positive outcome following the intervention was a small increase in initial knee flexion angle (Tables 1-3) and greater PFC mean horizontal braking force for CUT90. These technical changes are likely attributed to the coaching cues to "cushion over weight acceptance" and "slam on the brakes". Critically, however, increased initial and peak knee abduction angles were observed following the intervention (Tables 1-3). Sigward and Powers (39) suggest that an internally rotated lower-extremity position might be adopted by athletes to encourage the centre of mass of the body further away from the centre of pressure, and to facilitate the directional change to the intended direction of travel through a combination of rotations of the lower-limb joints. This finding may have been partially attributed to the cue to "lean towards the intended direction of travel". Although this cue was intended to alter trunk kinematics, athletes may have repositioned their lower-limb for more effective alignment towards the intended direction of travel, as evidenced by the moderate increases in initial foot progression angle (Tables 1-3). Results from previous research show no meaningful relationships between knee abduction angle and faster cutting performance (20, 33). Nevertheless, these findings highlight the difficulty in improving frontal plane control during cutting using technical cues only. Potentially, athletes would benefit from supplemental external hip rotator strengthening to improve frontal plane knee control during side-stepping (28, 37, 40).

Uniquely, the results from this study provide insight into which potential side-step cutting technical and mechanical variables increase and decrease knee joint loads (Table 4), and therefore could be used to inform future directions of training. Specifically, peak and initial knee abduction angle decreases were moderately to largely associated with reduced CUT45 and CUT90 peak KAMs and KIRMs. Additionally, increased initial knee flexion angles were moderately associated with reductions in CUT45 KAMs, while decreased lateral trunk flexion was moderately associated with CUT45 KIRMs decreases, and FFC vertical braking force decreases were moderately associated with CUT45 KAMs and CUT90 KIRMs reductions. Finally, FFC velocity decreases were moderately associated with CUT90 KAMs reductions. Consequently, these aforementioned variables are specific deficits to target in future training interventions to reduce multiplanar side-step knee joint loads (15, 17).

As COD biomechanical demands are angle- and task-dependent (14), caution is advised extrapolating the findings from this study to CODs of different angles and actions. Further research is necessary that investigates the effect of COD technique modification on sharper CODs and different COD actions in different populations. Unfortunately, no strength or body composition data was collected in this study. Thus, it is uncertain whether athletes with superior strength or body composition may have responded more favourably to the technique modification intervention, with weaker athletes potentially unable to adopt the desired postures and targeted technical modifications in this intervention. Future research is needed which accounts for strength and body composition following COD technique modification.

Due to time constraints, there was no initial pre-screening of individuals to specifically identify targeted deficits to inform technique modification training. Moreover, increased muscle activation of the hamstrings, gluteal muscles, and soleus, may have the potential to help unload the knee ligaments (7, 30). The present study did not monitor changes in muscle activation and is thus a future direction of research. Although this study aimed to examine the biomechanical effects of COD technique modification on ACL injury risk loading, in applied settings, athletes would however perform a mixed, multicomponent training program (14, 37) which incorporates strength, balance, trunk control, plyometrics, and COD/agility training, and this is recommended for ACL injury mitigation (15, 37). Therefore, future research which determines the effects of a mixed multicomponent training intervention on COD biomechanics is needed to increase the ecological validity to "real-world" environments. Lastly, it is unknown whether the technique can be maintained for extensive periods and it is unclear what happens to cutting biomechanics when this form of training is discontinued.

PRACTICAL APPLICATIONS

This is the first study to examine the biomechanical effects of a COD technique modification intervention on surrogates of ACL injury risk while containing a CG. Based on group means, COD technique modification was ineffective regarding potential injury risk. However, considerable individual variation was observed (i.e., positive and negative responders). Generally, subjects who displayed initially high multiplanar knee joint loads and thus considered potentially "high-risk", responded positively and demonstrated reductions in knee joint loads; highlighting the importance of an individual approach when monitoring training intervention effectiveness. Conversely, subjects with initially low multiplanar knee joint loads tended to increase their multiplanar knee joint loads post-intervention, albeit to levels considered not potentially hazardous or "high-risk". COD technique modification training is a simple, effective training method, requiring minimal equipment that can reduce knee joint loads in "higher-risk" subjects without compromising performance. Practitioners can consider incorporating this form of training (2 × 30-minute sessions a week) simply and easily into their pitch- or court-based training programs to mitigate ACL injury risk.

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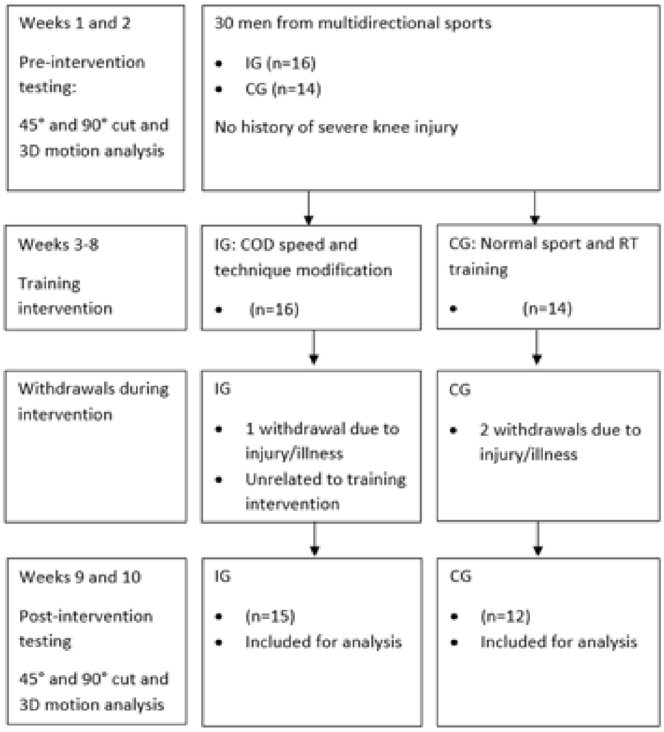

Figure 1. Flow diagram of participant participation throughout all stages of the intervention study. IG: Intervention group; CG: Control group; RT: Resistance training.

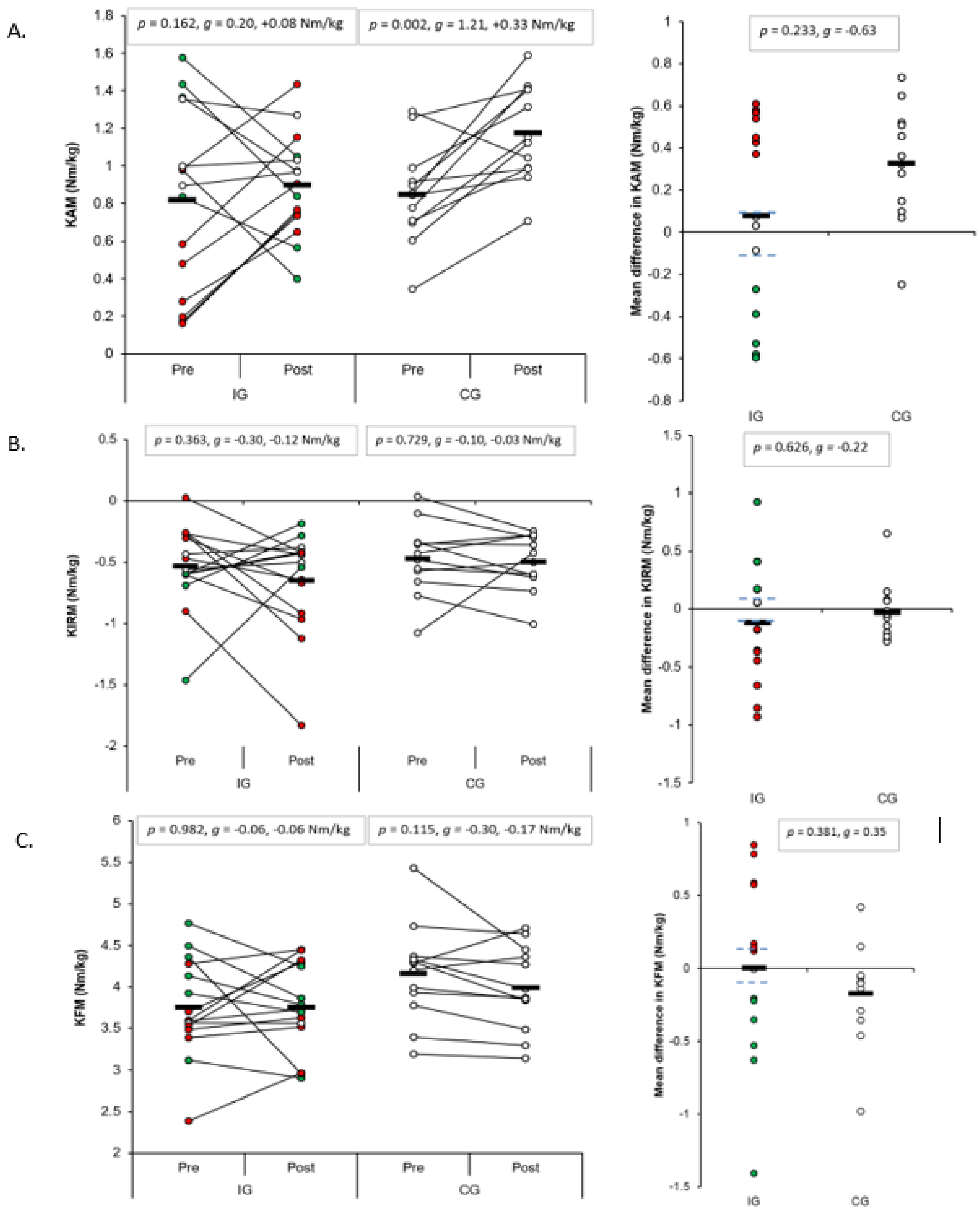

Figure 2. Pre-to-post changes in CUT45 multiplanar knee joint loads. A: KAM; B: KIRM; C: KFM. IG: Intervention group; CG: Control group; KAM: Knee abduction moment; KIRM: Knee internal rotation moment; KFM: Knee flexion moment; green = positive responder; red = negative responder; white = non-responder; blue line = SWC

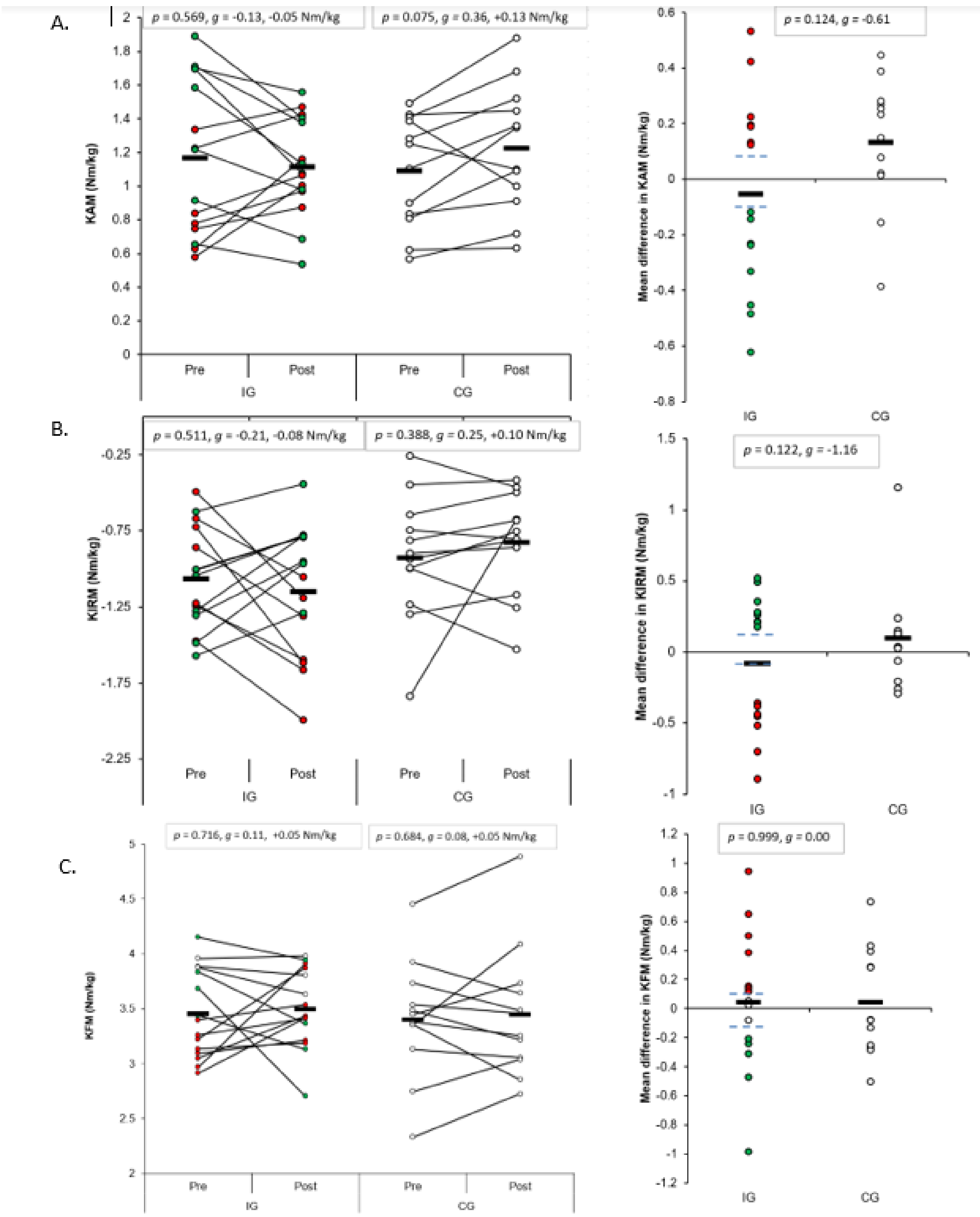

Figure 3. Pre-to-post changes in CUT90 injury risk multiplanar knee joint loads. A: KAM; B: KIRM; C: KFM. IG: Intervention group; CG: Control group; KAM: Knee abduction moment; KIRM: Knee internal rotation moment; KFM: Knee flexion moment; green = positive responder; red = negative responder; white = non-responder; blue line = SWC.

Table 1. Two-way mixed ANOVAs for CUT45 injury risk variables

Variable	CUT45 Group (interaction)			CUT90 Group (interaction)		
	p value	η2	power	*p* value	η2	power
peak KAM	0.116	0.096	0.346	0.124	0.092	0.334
peak KIRM	0.575	0.013	0.085	0.292	0.044	0.179
peak KFM	0.381	0.031	0.138	0.998	0.000	0.050
peak KAA	0.405	0.028	0.129	0.099	0.105	0.377
IC KAA	0.267	0.049	0.194	0.290	0.045	0.180
PFC mean HBF	-	-	-	0.124	0.092	0.335
FFC peak VBF	0.973	0.000	0.050	0.534	0.016	0.093
Lateral trunk flexion – IC	0.585	0.012	0.083	0.880	0.001	0.052
IFPA – IC	0.396	0.029	0.132	0.007*	0.258	0.810
Lateral foot plant distance - IC	0.235	0.056	0.216	0.837	0.002	0.055
HRA - IC	0.183	0.070	0.261	0.833	0.002	0.055
peak HRA	0.557	0.014	0.088	0.752	0.004	0.061
FFC peak KFA	0.046*	0.150	0.523	0.681	0.007	0.069
FFC IC KFA	0.349	0.035	0.151	0.360	0.034	0.146
FFC KFA ROM	0.049*	0.147	0.513	0.045*	0.151	0.528
Velocity at FFC	0.002*	0.330	0.921	0.470	0.021	0.109

: GCT: Ground contact time; KAM: Knee abduction moment; KIRM: Knee internal rotation moment; KFM: Knee flexion moment; KAA: K uction angle; IC: Initial contact; VBF: Vertical braking force; IFPA: Initial foot progression angle; KFA: Knee flexion angle; HRA: Hip rota angle; ROM: Range of motion; IC: Initial contact; FFC: Final foot contact; PFC: Penultimate foot contact *: $p \leq 0.05$; **: $p \leq 0.001$

Trivial η2 (< 0.010)	**Small η2 (0.010-0.059)**	**Medium η2 (0.060-0.149)**	**Large η2 (≥ 0.150)**

Table 2. CUT45 Pre-to-post changes in injury risk variables for IG and CG

	Variable	Pre		Post			Hedges' *g* effect size		Mean difference		SWC	Ratio to SWC	Individual r (Positive, non,
		Mean	SD	Mean	SD	*p*	*g*	± CI	Mean	SD			
	peak KAM (Nm/kg)	0.82	0.49	0.90	0.27	0.162	0.20	0.72	0.08	0.46	0.10	0.8	5-3-
	peak KIRM (Nm/kg)	-0.53	0.34	-0.65	0.42	0.363	-0.30	0.72	-0.12	0.51	0.07	1.7	5-2-
G	peak KFM (Nm/kg)	3.75	0.60	3.76	0.53	0.982	0.01	0.72	0.00	0.60	0.12	0.0	6-1-
	peak KAA (˚)	-9.4	5.5	-11.7	4.1	0.020*	-0.44	0.72	-2.2	4.5	1.1	2.0	4-3-
	IC KAA (˚)	2.7	5.4	-2.5	3.5	0.047*	-1.12	0.77	-5.2	4.7	1.1	4.8	0-3-1
	peak KAM (Nm/kg)	0.85	0.26	1.17	0.26	0.002*	1.21	0.87	0.33	0.28	0.05	6.2	1-0-1
	peak KIRM (Nm/kg)	-0.47	0.29	-0.50	0.23	0.729	-0.10	0.80	-0.03	0.26	0.06	0.4	4-2-
G	peak KFM (Nm/kg)	4.16	0.59	3.99	0.51	0.115	-0.30	0.80	-0.17	0.34	0.12	1.4	5-5-
	peak KAA (˚)	-10.3	6.8	-14.1	6.3	0.018*	-0.54	0.81	-3.7	4.6	1.4	2.7	1-2-
	IC KAA (˚)	2.1	3.7	-1.3	3.7	0.003*	-0.90	0.84	-3.4	3.2	0.7	4.6	0-2-1
	FFC peak VBF (BW)	4.02	0.95	4.14	1.08	0.566	0.11	0.72	0.12	0.77	0.19	0.6	5-2-
	Lateral trunk flexion – IC (˚)	-21.9	6.2	-21.6	8.3	0.877	0.04	0.72	0.3	8.3	1.2	0.3	8-0-
	IFPA – IC (˚)	-1.6	7.1	3.3	6.4	0.018*	0.70	0.74	4.8	7.0	1.4	3.4	4-1-1
	Lateral foot plant distance – IC (m)	-0.390	0.028	-0.403	0.029	0.160	-0.46	0.73	-0.013	0.035	0.006	2.4	5-1-
G	HRA - IC (˚)	7.9	7.0	11.8	6.6	0.014*	0.56	0.73	4.0	5.4	1.4	2.8	9-4-
	peak HRA (˚)	5.3	7.6	7.9	7.2	0.094	0.34	0.72	2.6	5.6	1.5	1.7	8-4-
	FFC peak KFA (˚)	54.8	6.1	52.2	4.6	0.066	-0.46	0.73	-2.6	5.0	1.2	2.1	3-3-
	FFC IC KFA (˚)	27.4	6.4	29.8	4.4	0.063	0.44	0.72	2.5	4.7	1.3	1.9	9-3-
	FFC KFA ROM (˚)	27.4	8.9	22.4	7.7	0.004*	-0.59	0.73	-5.0	5.8	1.8	2.8	1-5-
	Velocity at FFC (m/s)	5.08	0.29	5.41	0.29	0.001**	1.10	0.77	0.33	0.29	0.06	5.6	1-1-1
	FFC peak VBF (BW)	3.40	1.05	3.51	1.18	0.272	0.09	0.80	0.11	0.50	0.21	0.5	2-4-
	Lateral trunk flexion – IC (˚)	-19.6	9.2	-20.7	9.4	0.270	-0.11	0.80	-1.1	3.2	1.8	0.6	3-3-
	IFPA – IC (˚)	-0.3	5.5	2.6	5.5	0.015*	0.52	0.81	3.0	3.2	1.1	2.7	2-2-
	Lateral foot plant distance - IC (m)	-0.370	0.045	-0.370	0.004	0.917	0.01	0.80	0.001	0.022	0.009	0.1	2-5-
G	HRA - IC (˚)	8.0	3.6	9.3	6.3	0.330	0.24	0.80	1.3	4.4	0.7	1.8	9-0-
	peak HRA (˚)	5.9	3.3	7.2	6.5	0.372	0.25	0.80	1.4	5.0	0.7	2.0	8-1-
	FFC peak KFA (˚)	57.1	4.6	57.1	4.1	0.960	0.01	0.80	0.1	3.7	0.9	0.1	6-3-
	FFC IC KFA (˚)	27.4	6.8	28.4	5.9	0.319	0.14	0.80	0.9	3.1	1.4	0.7	6-4-
	FFC KFA ROM (˚)	29.7	7.7	28.8	6.2	0.483	-0.12	0.80	-0.9	4.2	1.5	0.6	4-4-
	Velocity at FFC (m/s)	5.04	0.31	4.95	0.44	0.347	-0.24	0.80	-0.09	0.33	0.06	1.5	6-2-

inal foot contact; KAM: Knee abduction moment; KIRM: Knee internal rotation moment; KFM: Knee flexion moment; KAA: Knee abduction angle; IC: Initial contact; IG: Intervention group; CG: Control grou nterval; SD: Standard deviation; SWC: Smallest worthwhile change; ES : Effect size; BW: Body weight; VBF: Vertical braking force; IFPA: Initial foot progression angle; KFA: Knee flexion angle; HRA: Hip rotation a tion; IC: Initial contact; *: $p \leq 0.05$; **: $p \leq 0.001$

Trivial ES (≤ 0.19)	Small ES (0.20-0.59)	Moderate ES (0.60-1.19)	Large ES (1.20-1.99)

Table 3. CUT90 Pre-to-post changes in injury risk variables for IG and CG

	Group	Variable	Pre		Post			Hedges' *g* effect size		Mean difference		SWC	Ratio to SWC	Individual response (Positive, non, negative)
			Mean	SD	Mean	SD	*p*	*g*	± CI	Mean	SD			
Primary outcome variables		peak KAM (Nm/kg)	1.17	0.46	1.11	0.29	0.569	-0.13	0.72	-0.05	0.34	0.09	0.6	8-0-7
		peak KIRM (Nm/kg)	-1.07	0.34	-1.15	0.43	0.511	-0.21	0.72	-0.08	0.47	0.07	1.2	8-0-7
	IG	peak KFM (Nm/kg)	3.46	0.41	3.50	0.36	0.716	0.11	0.72	0.05	0.47	0.08	0.6	5-3-7
		peak KAA (˚)	-11.9	6.0	-15.6	5.2	0.023*	-0.64	0.73	-3.7	4.8	1.2	3.1	3-0-12
		IC KAA (˚)	3.8	3.8	0.1	4.5	<0.001**	-0.86	0.75	-3.7	2.2	0.8	4.9	0-0-15
		peak KAM (Nm/kg)	1.09	0.33	1.22	0.38	0.075	0.36	0.81	0.13	0.24	0.07	2.0	2-2-8
		peak KIRM (Nm/kg)	-0.92	0.41	-0.83	0.34	0.388	0.25	0.80	0.10	0.38	0.08	1.2	6-3-3
	CG	peak KFM (Nm/kg)	3.41	0.54	3.45	0.60	0.684	0.08	0.80	0.05	0.37	0.11	0.4	5-2-5
		peak KAA (˚)	-13.2	8.0	-15.3	6.8	0.223	-0.27	0.80	-2.1	5.5	1.6	1.3	2-2-8
		IC KAA (˚)	2.9	3.6	0.8	4.6	0.070	-0.50	0.81	-2.1	3.7	0.7	2.9	2-2-8
Secondary outcome variables		PFC mean HBF (BW)	-0.59	0.13	-0.65	0.16	0.024*	-0.39	0.72	-0.06	0.09	0.03	2.2	9-4-2
		FFC peak VBF (BW)	3.03	0.87	3.10	0.81	0.307	0.07	0.72	0.06	0.32	0.17	0.4	3-7-5
		Lateral trunk flexion – IC (˚)	-20.5	8.7	-21.1	8.0	0.768	-0.07	0.72	-0.6	8.3	1.7	0.4	6-2-7
		IFPA – IC (˚)	11.1	9.3	18.7	5.6	0.002*	0.97	0.76	7.6	7.7	1.9	4.1	2-0-13
		Lateral foot plant distance - IC (m)	-0.320	0.035	-0.318	0.038	0.822	0.07	0.72	0.003	0.048	0.007	0.4	6-1-8
	IG	HRA - IC (˚)	11.8	8.8	13.1	7.0	0.302	0.16	0.72	1.3	4.6	1.8	0.7	7-5-3
		peak HRA (˚)	10.3	8.1	11.9	6.8	0.183	0.21	0.72	1.6	4.4	1.6	1.0	6-6-3
		FFC peak KFA (˚)	62.7	5.9	61.7	5.2	0.518	-0.17	0.72	-1.0	5.7	1.2	0.8	6-2-7
		FFC IC KFA (˚)	23.8	5.4	26.6	4.4	0.029*	0.54	0.73	2.8	4.4	1.1	2.5	10-2-3
		FFC KFA ROM (˚)	38.9	6.6	35.2	5.7	0.018*	-0.59	0.73	-3.7	5.4	1.3	2.8	3-3-9
		Velocity at FFC (m/s)	3.41	0.27	3.47	0.32	0.396	0.18	0.72	0.05	0.24	0.05	1.0	5-2-8
		PFC mean HBF (BW)	-0.57	0.15	-0.58	0.11	0.616	-0.07	0.80	-0.01	0.06	0.03	0.3	1-1-10
		FFC peak VBF (BW)	2.69	1.09	2.66	0.87	0.530	-0.03	0.80	-0.03	0.41	0.22	0.1	3-6-3
		Lateral trunk flexion – IC (˚)	-14.8	8.6	-15.9	7.2	0.544	-0.13	0.80	-1.1	6.0	1.7	0.6	5-2-5
		IFPA – IC (˚)	16.7	11.9	16.8	13.6	0.917	0.01	0.80	0.1	4.8	2.4	0.1	4-3-5
		Lateral foot plant distance - IC (m)	-0.289	0.054	-0.282	0.073	0.541	0.10	0.80	0.006	0.035	0.011	0.6	6-2-4
	CG	HRA - IC (˚)	11.6	7.4	13.5	9.7	0.515	0.21	0.80	1.9	9.7	1.5	1.3	8-0-4
		peak HRA (˚)	9.1	7.0	9.9	9.2	0.766	0.09	0.80	0.8	8.8	1.4	0.6	7-1-4
		FFC peak KFA (˚)	66.0	5.1	65.9	6.5	0.948	-0.02	0.80	-0.1	5.1	1.0	0.1	6-3-3
		FFC IC KFA (˚)	23.1	4.6	24.5	5.2	0.152	0.27	0.80	1.4	3.1	0.9	1.5	7-2-3
		FFC KFA ROM (˚)	42.9	6.8	41.4	8.3	0.396	-0.19	0.80	-1.5	5.7	1.4	1.1	5-1-6
		Velocity at FFC (m/s)	3.46	0.25	3.46	0.29	0.925	-0.02	0.80	0.00	0.15	0.05	0.1	3-5-4

Key: FFC: Final foot contact; KAM: Knee abduction moment; KIRM: Knee internal rotation moment; KFM: Knee flexion moment; KAA: Knee abduction angle; IC: Initial contact; BW: Body weight; VBF: Vertical braking force; HBF: Horizontal braking force; IFPA: Initial foot progression angle; KFA: Knee flexion angle; HRA: Hip rotation angle; ROM: Range of motion; IC: Initial contact; FFC: Final foot contact; PFC: Penultimate foot contact; IG: Intervention group; CG: Control group; CI : 95% Confidence interval; SD: Standard deviation; SWC: Smallest worthwhile change; ES: Effect size; *: $p \leq 0.05$; **: $p \leq 0.001$

Trivial ES (≤ 0.19)	Small ES (0.20-0.59)	Moderate ES (0.60-1.19)	Large ES (1.20-1.99)

Table 4. CUT45 and CUT90 associations between changes in performance and injury risk variables with changes in technical ar mechanical variables

CUT45	Associated with	Correlation value with 95% Confidence intervals	Descriptor
Decreases in peak KAM	1. Decreased peak KFM 2. Decreased peak KAA 3. Decreased IC KAA 4. Decreased KIRM 5. Decreased IFPA	1. $\rho = 0.611 \pm 0.356$, $p = 0.016$ 2. $\rho = -0.771 \pm 0.246$, $p = 0.001$ 3. $\rho = -0.479 \pm 0.420$, $p = 0.071$ 4. $\rho = -0.495 \pm 0.413$, $p = 0.061$ 5. $\rho = 0.600 \pm 0.362$, $p = 0.018$	1. Large 2. Very large 3. Moderate 4. Moderate 5. Large
Decreases in peak KIRM	1. Decreased peak KFM 2. Decreased peak KAM 3. Decreased IC lateral trunk flexion	*1.* $r = -0.495 \pm 0.413$, $p = 0.061$ *2.* $\rho = -0.495 \pm 0.413$, $p = 0.061$ *3.* $r = 0.485 \pm 0.418$, $p = 0.067$	1. Moderate 2. Moderate 3. Moderate
CUT90	**Associated with**	**Correlation value with 95% Confidence intervals**	**Descriptor**
Decreases in peak KAM	1. Decreased peak KFM 2. Increased PFC mean HBF 3. Decreased velocity at FFC	1. $r = 0.403 \pm 0.448$, $p = 0.011$ 2. $r = -0.430 \pm 0.439$, $p = 0.110$ 3. $r = 0.496 \pm 0.413$, $p = 0.060$	1. Moderate 2. Moderate 3. Moderate
Decreases in peak KIRM	1. Decreased peak KAA 2. Decreased IC KAA 3. Decreased lateral foot plant distance 4. Decreased FFC peak VBF	*1.* $r = 0.446 \pm 0.433$, $p = 0.096$ *2.* $r = 0.495 \pm 0.413$, $p = 0.061$ 3. $r = 0.490 \pm 0.415$, $p = 0.064$ 4. $r = -0.468 \pm 0.424$, $p = 0.079$	1. Moderate 2. Moderate 3. Moderate 4. Moderate

Key: KAM: Knee abduction moment; KIRM: Knee internal rotation moment; VBF: Vertical braking force; KFM: Knee flexion momer KFA: Knee flexion angle; IC: Initial contact; FFC: Final foot contact; PFC: Penultimate foot contact; IFPA: Initial foot progression angle