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Biomechanical Associates of Performance and Knee Joint Loads During an 70-90° Cutting Maneuver in Sub-Elite Soccer Players

ABSTRACT

The aim of this study was to explore the ‘performance-injury risk’ conflict during cutting, by examining whole-body joint kinematics and kinetics that are responsible for faster change of direction (COD) performance of a cutting task in soccer players, and to determine whether these factors relate to peak external multi-planar knee moments.34 male soccer players (age: 20 ± 3.2 yrs; mass: 73.5 ± 9.2 kg; height: 1.77 ± 0.06 m) were recruited to investigate the relationships between COD kinetics and kinematics with performance and multi-planar knee joint moments during cutting. Three-dimensional motion data using 10 Qualisys Oqus 7 infrared cameras (240 Hz) and ground reaction force (GRF) data from two AMTI force platforms (1200 Hz) were collected to analyze the penultimate (PFC) and final (FFC) foot contacts. Pearson’s or Spearman’s correlations coefficients revealed performance time (PT), peak external knee abduction moment (KAM) and peak external knee rotation moment (KRM) were all significantly related ($P < 0.05$) to horizontal approach velocity (PT: $\rho = -0.579$; peak KAM: $\rho = 0.414$; peak KRM: $R = -0.568$), and FFC peak hip flexor moment (PT: $\rho = 0.418$; peak KAM: $\rho = -0.624$; peak KRM: $\rho = 0.517$). PT was also significantly ($p < 0.01$) associated with horizontal exit velocity ($\rho = -0.451$), and, notably, multi-planar knee joint loading (peak KAM: $\rho = -0.590$; peak KRM: $\rho = 0.525$; peak KFM: $\rho - 0.509$). Cohen’s D effect sizes (*d*) revealed that faster performers demonstrated significantly greater ($P < 0.05$; $d = 1.1 – 1.7$) multi-planar knee joint loading, as well as significantly greater ($P < 0.05$; $d = 0.9 – 1.2$) FFC peak hip flexor moments FFC, PFC average horizontal GRFs, and peak knee adduction angles. To conclude, mechanics associated with faster cutting performance appear to be ‘at odds’ with lower multi-planar knee joint loads. This highlights the potential performance-injury conflict present during cutting.

Key words: change of direction; anterior-cruciate ligament knee injury; whole-body kinematics; ground reaction forces; external knee abduction moments.

INTRODUCTION

Change of direction (COD) maneuvers are frequent actions that occur in soccer (2). Notational analysis in FA Premier League soccer players has found that an average of 609 turns occurring within 0-90° can be made during a single game (2). Thus, the ability to quickly change direction in response to constantly changing circumstances (i.e. opposition, ball) can be considered a pivotal component to successful performance in multi-directional sports, such as soccer (44). That said, COD maneuvers, such as cutting, have been identified as key actions that are associated with non-contact anterior cruciate ligament (ACL) injuries (3,13,47) with amplified multi-planar knee joint loading (i.e., flexion, rotational, and abduction loading) whilst the foot is planted often reported (5,6,17,26,45). Such loads are associated with increased strain on the ACL (37,38,45). Less is understood regarding the mechanics concerning optimal performance in such actions, with only a handful of studies having examined the mechanics of faster COD tasks (4,10,17,31,36). Resultant research findings have demonstrated that medial trunk rotation (31), as well as braking and propulsive forces in shorter ground contact times result in faster COD performance (10,41). This holds great importance for coaches to develop training programs that improve COD performance whilst reducing the risk of ACL injury.

The mechanical determinants of performance have been previously elucidated (10,18,41–43); however, there are a limited number of studies to date that have examined the combination of kinetic, kinematic, and technical factors which determine COD speed performance (31). Marshall *et al.* (31) explored a whole-body analysis of a 75° cutting task, in which they uncovered five key biomechanical performance associates: peak ankle extensor moment and power, pelvic frontal plane control, trunk rotation towards the intended direction of movement, and ground contact time (GCT). The authors suggested the development of force production about the ankle, improved proprioceptive control of the pelvis during single-limb support, and rotation of the torso towards the intended direction were all technique factors contributing to superior COD performance.

Research in relation to cutting technique injury risk factors has received greater attention (5,6,18,24,26,29,40), with frontal plane knee mechanics being recognized as key characteristics associated with ACL injuries. A number of studies have suggested that initial knee adduction angle (KAA) (26,29), lateral leg plant distance (5,6,17,26) and initial lateral trunk flexion (5,6,24,26) are technique factors which, coupled with high plant foot GRF vectors, likely dictates the magnitude of external knee abduction moments (KAMs). Consequently, addressing these aforementioned determinants of KAMs could be a viable method to reduce knee joint loading and subsequent ACL strain during cutting (5,6,18,24,26,29,40).

COD is a multi-step action with which preliminary deceleration is required prior to turn initiation (10,11,25,26). It seems that if a greater proportion of forward momentum can be overcome by applying large GRFs during the penultimate foot contact (PFC), then the GRFs experienced in the final foot contact (FFC) prior to direction change may be mitigated and subsequently reduce the KAMs experienced (11,25,26). Equally, recent findings have reported that this deceleration strategy may also be beneficial for COD performance, due to the subsequent decreased time spent braking in the FFC (10). Although insightful, this study was limited to solely investigating COD kinetics in an isolated 180° pivot. As such, a more comprehensive biomechanical assessment of the role of the PFC in relation to cutting performance is warranted.

Havens and Sigward (17) explored the potential 'performance-injury risk' conflict, investigating the joint characteristics related to completion times of 45° and 90° cuts, with the aim of revealing which factors were associated with performance and frontal plane knee joint loading (i.e., peak KAMs). From this, "medial-lateral center of mass-center of pressure distance" (analogous to lateral leg plant distance; Table 1) was found to be the only variable that was predictive of both performance times and peak KAM (45°). Although definitions of lateral leg plant (LLP) distance may differ slightly within the reported literature (e.g., whether this distance is relative to pelvic position or to the frontal plane), the findings of Haven's (17) work highlight the role LLP distance as a performance factor (23) and in increased knee joint loading (5,6,17,26) of COD actions. Clearly, this conflict needs to be investigated further in order to improve ACL injury mitigation and COD speed training recommendations. Furthermore, Havens and Sigward (17) presented different findings in relation to their 90° cutting task, (i.e., internal knee extensor moment and hip rotation angle were associated with performance time and peak KAM), so it could be stipulated that the recommended technique for 45° cutting (i.e., emphasizing sagittal plane motion as a product of decreased torso and lower-body positioning in the frontal plane) may not be applicable to a 90° cut, and may reduce performance times without alleviating heightened mechanical knee joint loading.

The aim of this study was to investigate the whole-body joint kinematics and kinetics that are responsible for faster cutting performance in professional, semi-professional, and collegiate soccer players, and whether these factors are related to multi-planar knee joint loads (i.e., peak KAM, KRM, and KFM), and thus potential ACL injury risk. This was approached using three primary objectives: (a) to determine which biomechanical factors were associated with faster COD performance of an 70-90° cutting maneuver; (b) to identify which of these variables were associated with peak KAM, KRM, and KFM; and (c) to compare the biomechanical differences between faster and slower performers during the 70-90° cutting task. It was hypothesized that LLP distance, medial-lateral GRFs and PFC kinetics would be associated with faster completion times, whilst LLP distance and PFC kinetics would be related to both performance and multi-planar knee joint loading.

METHODS

Experimental Approach to the Problem

A cross-sectional study design was used to evaluate whole-body kinematics and kinetics during a 70-90° cutting maneuver using 3D-motion and GRF analysis over a single testing session. Pearson's or Spearman's correlation coefficients were used to evaluate the association between pre-determined biomechanical factors of performance (Table 1). Biomechanical differences between faster and slower performers during the maneuver were assessed using independent T-tests and Cohen's d effect sizes, as used previously (20). A minimum sample size of 33 participants was determined from an *a-priori* power analysis using G-Power (Version 3.1, University of Dusseldorf, Germany) based upon a previously reported correlation value of 0.45 (LLP to KAM), a power of 0.8 and type 1 error or alpha level 0.05 (12).

Subjects

Thirty-four male soccer players (age: 20 ± 3.2 yrs; mass: 73.5 ± 9.2 kg; height: 1.77 ± 0.06 m) participated in this study. These were considered to be experienced high-standard players (i.e., collegiate, semi-professional, or professional), who were all approaching the mid-point of their respective playing seasons. Participants were required to be free from injury and/or display no chronic physical pathologies that may have affected performance of the task. Before completion of the task, the outline of the testing procedure was communicated and written informed consent from all participants was acquired. Parental/guardian consent was ascertained for participants who were under the age of 18 and approval for the study was granted by the University's ethical committee.

Procedures

Cutting Task

Participants were first required to perform a standardized warm-up, which included 5 minutes of heart rate elevation exercise (i.e., 6 low-intensity laps of the performance track) followed by dynamic stretches and activation exercises (i.e., bodyweight squats, walking lunges, bilateral jumps), before executing 5-6 familiarization trials of the cutting task. To record performance time (PT) of the 70-90° cut, two pairs of Brower single beam timing gates (Draper, UT) were used and aligned to approximately hip height (49) and two force platforms were embedded within the track. The initial set of timing gates were positioned 5 m away from the center of the final force platform (FP), with another pair of timing gates set up 3 m between 70° and 90° to the center of the FP to mark the finishing point of the task; this presented the athlete with a cutting 'window' with which to accelerate through (Figure 1). Participants were then instructed to perform six 'good' trials of the cutting task, where they would aim to sprint at maximal effort through the first set of timing gates, arriving and planting their left foot on the first FP (i.e., PFC), and then their right foot on the final FP (i.e., FFC), before instantaneously cutting 70-90° to the left and running through the final set of timing gates (Figure 1). For a trial to be considered 'good', the following criteria was set: (1) a straight approach into the turn without curvature/premature turning prior to FFC; (2) FFC landing in the central portion of the final FP, ensuring a homogenous distance of travel between trials.

****Figure 1 near here****

Biomechanical Analyses

To approximate motion of body segments during the cutting task, reflective markers (14 mm spheres) were fixed bilaterally, using double-sided adhesive tape, on the following bony landmarks: 5th, 2nd and 1st metatarsal heads, medial and lateral malleoli, medial and lateral epicondyles, greater trochanter, anterior superior iliac spine, posterior superior iliac spine, iliac crest, acromion process, mid-clavicle and 7th cervical vertebrae. A ‘cluster set’ (i.e., 4 retro-reflective markers attached to a lightweight rigid plastic shell) was also fastened to the participant’s thighs and shins (both left and right) in order to approximate segmental motion during dynamic trials. Ten Qualisys Oqus 7 (Gothenburg, Sweden) infrared cameras (240 Hz) were used to record the three-dimensional motions of the markers whilst performing the cutting task, interfaced through Q-Track Manager software (version 1.10.282, Gothenburg, Sweden). Two AMTI (600 mm X 900 mm) (Advanced Mechanical Technology, Inc, Watertown, MA) FP’s (Model number: 600900) embedded into the running track were used to record GRFs from both the final and penultimate foot contacts. FP sample frequency was set at 1200 Hz.

From a static trial, a 6-degree-of-freedom kinematic model of the lower extremity and trunk was created for each participant, including trunk, pelvis, thigh, shank and foot, using Visual 3D software (C-motion, version 3.90.21). This kinematic model was used to quantify the motion at the hip, knee and ankle joints using a Cardan angle sequence (15). The local coordinate system is defined at the proximal joint center for each segment. The static trial position is designated as the participant’s neutral (anatomical zero) alignment, and subsequent kinematic measures were related back to this position. Lower limb joint moments were calculated using an inverse dynamics approach (48) through Visual3d software (C-motion, version 3.90.21) and were defined as external moments. Based on the recommendations from Roewer *et al.* (35) and residual analysis, joint coordinate and force data were smoothed in visual 3D with a Butterworth low pass digital filter with pre-determined cut-off frequencies of 12 and 25 Hz, respectively. Segmental inertial characteristics were estimated for each participant (7). The model utilized a CODA pelvis orientation (1) to define the location of the hip joint center. The knee and ankle joint centers were defined as the mid-point of the line between lateral and medial markers. The trials were time-normalized for each participant, with respect to the GCT of the 70-90° cut. Peak and average GRF, peak joint moments, and peak joint and segment angles with respect to range of motion were classified during the plant phase (i.e., initial contact to toe-off; Table 1). Initial contact was defined as the instant after ground contact that the vertical GRF (vGRF) was higher than 20 N and end of contact was defined as the point where the vGRF subsided past 20 N for both PFC and FFC (Table 1). The weight acceptance phase of ground contact was defined as from the instant of initial contact (vGRF > 20N) to the point of maximum knee flexion during ground contact, as used previously (17,25). The push-off phase was determined as the instant after maximum knee flexion to subsequent toe-off (vGRF < 20N). Participant ‘true’ cut angle and participant center of mass (COM) horizontal velocity during approach and exit of the maneuver were also calculated (Table 1). Definitions of all biomechanical variables of interest are provided in ‘Table 1’ and have previously demonstrated good reliability (ICC’s ≥ 0.70; CV% $\leq 15\%$) in pilot work from our lab, which used a subset of this sample (n = 10) (8).

****Insert Table 1 here****

Statistical Analyses

All statistical analyses from the data collected were performed using SPSS statistical analysis software (version 23.0, SPSS, Ince., IL, USA) and Microsoft Excel (version 2016, Microsoft Corp., Redmond, W.A., USA). Preliminary normality tests were taken in order to determine whether Pearson's product correlation or Spearman's rank correlation was to be used. These correlation tests were employed to determine which biomechanical variables (Table 1) of interest were associated with PT, exit velocity, peak KAM, peak KRM, and peak KFM during the 70-90° cut. Resultantly, correlation strength was based on the following parameters: 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 (1.0) (21). Additionally, independent sample T-tests or Mann-Whitney U tests were used for comparisons between 'fast' and 'slow' performers (i.e., fastest ten PTs vs. slowest ten PTs), similar to the procedures of previous research (10,43). Cohen's d effect sizes (*d*) were also implemented to determine the magnitude of differences in performance variables between fast and slow performers. Effect size magnitudes were described based on the following criteria: trivial (< 0.19), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), and very large (2.0–4.0) (22). P-values were Bonferroni corrected (i.e., multiplied by number of correlations explored) to avoid family-wise error, with significance set at $p<0.05$ following correction.

RESULTS

Descriptive statistics for each variable are presented in 'Table 2' and 'Table 3'. Performance time demonstrated large significant correlations with peak KAM, horizontal approach velocity, peak KRM, peak KFM ($P < 0.01$), and moderate significant correlations with horizontal exit velocity ($P = 0.007$) and peak hip flexor moment ($P = 0.014$; Table 2). Peak KAM demonstrated large significant correlations with peak hip flexor moment, performance time, peak KFM, peak KRM ($P < 0.01$), and a moderate significant correlation with horizontal approach velocity ($P = 0.015$; Table 2). Peak KRM demonstrated large significant correlations with average ML GRF FFC, average and peak hGRF FFC, horizontal approach velocity, performance time, peak hip flexion moment ($P < 0.01$), and moderate significant correlations with peak KFM, peak KAM, peak ML FFC and peak vGRF FFC ($P < 0.05$; Table 2). Peak KFM showed a moderate significant correlation with peak KAM and peak KRM ($P < 0.01$; Table 2). No significant relationships were found for peak/average HBFR and peak/average hGRF PFC between either PT, peak KAM, peak KRM or peak KFM.

Horizontal exit velocity showed large significant correlations with FFC GCT, LLP distance, peak ML FFC, horizontal approach velocity and average ML FFC ($P < 0.01$) (Table 3). Horizontal approach velocity displayed large significant correlations with average hGRF FFC, horizontal exit velocity, peak hGRF PFC, peak ML FFC, peak hip flexor moment, peak hGRF FFC, and moderate significant correlations with average hGRF PFC ($P = 0.004$) and peak vGRF PFC ($P = 0.013$) (Table 3).

Comparisons between fast and slow performers for performance variables, as well as kinetic and kinematic characteristics are presented in ‘Table 4’, ‘Table 5’ and ‘Table 6’, respectively. Large to very large significant differences between fast and slow performers for performance time ($P < 0.001$; d = - 3.0), horizontal approach velocity ($P < 0.001$; d = 2.0) and horizontal exit velocity ($p = 0.014$; d = 1.2) were observed. For the kinetic variables of interest, a large significant difference was observed for peak KRM ($P = 0.005$; d = - 1.7), and moderate significant differences between fast and slow performers for peak KAM ($P = 0.005$; d = 1.1), peak KFM ($P = 0.029$; d = 1.1), peak hip flexor moment ($P = 0.016$; d = -0.9), and average hGRF PFC ($P = 0.05$; d = - 0.9) were displayed. Although non-significant ($P > 0.05$), moderate effect sizes were observed for peak hGRF PFC (d = - 0.8), peak hGRF FFC (d = - 0.7), average hGRF FFC (d = - 0.8), peak ML FFC (d = 0.6). For the technique variables of interest, only peak KAA was found to be moderately different ($P = 0.042$; d = - 1.0) between fast and slow performers.

****Insert Table 2 here****

****Insert Table 3 here****

****Insert Table 4 here****

****Insert Table 5 here****

****Insert Table 6 here****

DISCUSSION

The aim of this investigation was to establish whether the technical and mechanical associates of a faster 70-90° cutting maneuver are at odds with the factors responsible for increased multi-planar joint loads at the knee. This study substantiates previous research (17), and further illustrates the conflict between performance and mechanical knee joint loading during cutting. Indeed, peak KAM, KRM and KFM were all significantly related to PT (Table 2) and were also significantly greater for fast performers compared to slow performers (Table 5). Furthermore, horizontal approach and exit velocity, and peak hip flexor moment (FFC) were all variables significantly correlated to faster cutting PTs; however, such variables were also correlated with heightened multi-planar knee joint loading (Table 2). Thus, these findings indicate that the biomechanical characteristics necessary for faster cutting are in direct conflict with those required to reduce knee joint loading and potential ACL strain.

This appears to be first study to conduct a multi-planar biomechanical analysis of knee joint loads during cutting that has been considered from both a performance and injury risk perspective (i.e., increased ACL strain). Previous investigations have typically focused on examining the isolated measure of KAMs in relation to injury risk or performance (5,6,18,24,26,29,40), whereas research which considers multi-planar loading of the knee is somewhat limited (6,24). This type of investigation is certainly warranted based on reports showing that ACL strain is amplified when combined sagittal, frontal and transverse knee moments are generated in contrast to uni-planar loading (38). That there were large to moderate relationships observed between peak KAM, peak KRM and peak KFM (Table 2) consolidates this notion and suggests that the biomechanical factors associated with peak KAMs may likely increase the overall mechanical loading experienced at the knee joint, and thus increased ACL knee injury risk.

Sagittal plane hip mechanics (i.e., peak hip flexor moment, peak KFM) were responsible for faster PTs and greater mechanical knee joint loading (Table 2), and were also significantly different between faster and slower performers (Table 5). This is in contrast the findings of Havens and Sigward (17), who found that frontal plane hip mechanics were performance predictors of a 90° cutting task. It is unclear how increased hip flexor moments would relate to increased knee joint loads, it can only be suggested that faster approach velocities (a correlate of PT, peak KAMs and peak KRMs) into the turn would produce higher GRFs and subsequently greater moments about the hip. Previous work (27,34), however, did find peak hip flexor moments to lower KAMs. The authors suggested (34) that an increased activation of the hip extensor musculature may have enabled a more controlled deceleration into the turn, implicating the role of eccentric strength for deceleration in the sagittal plane prior to direction change in sharper turns (27). Peak KFM was a factor related to both performance and mechanical knee joint loading (Table 2; Table 5) which agrees with the previous work Havens and Sigward (17). From a performance perspective, the knee extensor muscles will act eccentrically to reduce momentum of the system to enable a subsequent rapid transition to reaccelerate into the new intended direction (17). The mechanisms explaining KFM as a potential injury risk factor are less clear, with it being postulated that heightened sagittal knee joint loading may relate to larger shear forces acting on the knee joint during the task (17). It has also been argued that an increased quadriceps activation (i.e., greater peak KFM) may increase the strain on the ACL by increasing the anterior translation at the knee (14); namely, it may be the coupling of this anterior translation produced by the quadriceps with valgus and internal rotation moments that accentuates the loading risk associated with non-contact ACL injury (6), which would support the multi-planar nature of ACL strain injuries (38).

COM horizontal approach and exit velocities were both significantly related to PT, with the former also showing to be associated with knee joint loading (Table 2). High approach velocities have previously been found to contribute to increased KAMs in the FFC (32,46), which would be expected based on the increasingly higher forces that are generated with increased running velocities (46). Furthermore, higher velocities (27), peak accelerations and peak speeds during COD tasks of 45° and 90° have all been previously shown to determine COD performance (16). It is unsurprising that high running velocities corresponded with improved PTs, given that faster speeds equate to distances being covered in shorter time. These results, however, do add emphasis to the ‘performance-injury risk’ conflict apparent in cutting, as faster athletes experience greater loads, and thus potentially ACL strain. Accordingly, practitioners should aim to improve the approach velocities of athletes but acknowledge the concurrent increased knee joint loading that may coincide with these improvements.

In contrast to the work of Havens and Sigward (17) that only examined PT, the present study investigated the COM velocity during the approach and exit, which allowed for a COD velocity profile to be examined (16). As such, LLP distance, peak and average ML FFC, and horizontal approach velocity were all correlated with horizontal exit velocity (Table 3). LLP distance has been identified as a determinant of peak KAMs (5,6,17,26) and also as a performance determinant (17,23). When the foot is placed laterally further from the midline of the body during FFC, this causes the center of pressure to be positioned more laterally to the knee joint axis, thereby creating a larger moment arm for the intersegmental GRFs to act and subsequently amplify the KAMs sustained at the knee joint (17,40). This lateral translation will also act to accelerate the COM to the contralateral side (33), thus highlighting LLP as a correlate of performance. Practitioners should apply caution when modifying lateral foot plant distances to reduce injury risk (i.e., coaching a more medially oriented foot placement) (5,6), as athletes are less likely to adopt technique that puts constraints on performance.

The finding that both peak and average ML GRFs related to horizontal exit velocity may be explained by the mechanical principle which states that direction change is most effectively achieved when force is applied perpendicular to current direction of motion (30). Thus, a large ML GRF, generated with a large LLP distance, will maximize the frictional force applied and resultant exit velocity directed towards the intended direction of travel (40). Although the application of GRFs as performance (10,18,41–43) and injury risk (25,39,40) factors have been well documented, this study is one of only another (17) to have considered from a performance perspective the technical elements alongside GRF application which are required during different COD tasks. Larger horizontal propulsive forces have been previously shown to contribute to performance of a 180° pivoting maneuver (10), with the authors suggesting that athletes who apply horizontal forces more effectively are able to propel themselves into the new intended direction at higher velocities. Although different tasks were performed (i.e., 70-90° cut vs. 180° pivot), comparisons can still be made when the direction of travel is assessed in its mechanical terms; the dominant anterior-posterior kinetics during a 180° pivot may shift towards an increased demand on ML kinetics of the

70-90° cut. Therefore, it may be stipulated that athletes who elicit higher ML GRFs in the FFC enable greater propulsion into a more laterally directed exit (i.e., 70-90° cut) (23).

A number of GRF FFC properties were associated with peak KRM (Table 2) and, although non-significant, displayed small to moderate effect sizes between fast and slow performers (Table 5). These findings are in agreement with previous findings by Jones *et al.* (25) of a similar cutting angle that found horizontal GRF FFC properties were related to peak KAMs. This would be expected as heightened GRFs generated during FFC would correspond with increased overall mechanical loading at the knee (25,26,39). However, no relationships were found between any GRF PFC variables and mechanical knee joint loading, which is in contrast to the findings mentioned above (25). On the surface, this suggests that the braking characteristics in the PFC are not as important as previously suggested, which is perhaps surprising, considering COD tasks of a sharper nature (i.e., > 45°) have been shown to necessitate its role (10,27). It is worth noting, however, a moderate effect size for average hGRF PFC and a moderate yet non-significant effect size for peak hGRF PFC was observed between fast and slower performers (Table 5), which may provide some evidence for this braking strategy. Additionally, it should be acknowledged that the distance of this present study was notably shorter than used previously (i.e., 5 m vs. 10, 15 m), which has been shown to influence the involvement of braking characteristics in respective tasks (28). Furthermore, it cannot be dismissed that the reduced cutting angle undertaken in this investigation may have altered the braking kinetics demonstrated in the PFC, as shallower cutting angles may require lower reductions in momentum (achieved partly via greater hGRFs) before re-accelerating out of the turn (9,25). It has been stipulated that, during the PFC, GRFs are dissipated through flexion of the hip and knee joints (25,32), which occurs throughout the entire stance phase and through transition into the FFC. Resultantly, the participant’s COM is lowered and the right leg can be planted in front of the body (i.e., increasing the hGRF directed vector) (25). This PFC braking strategy may be useful from both performance and injury risk perspectives, as not only does the reduction in GRFs in the FFC subsequently reduce the peak KAMs experienced, but it also means less momentum needs to be dissipated during the FFC, which may reduce GCT during the FFC and allow for more rapid extension of the joints for propulsion out of the turn (10,19). This may explain the relationship observed between GCT FFC and exit velocity (Table 3), as well as the moderate, albeit non-significant, effect sizes observed between faster and slower performers (Table 5). These findings substantiate previous research which has suggested that shorter GCT FFC are factors of COD performance (10,18,41–43).

Interestingly, other than LLP distance, no technique variables had meaningful significant correlations with performance factors (PT/exit velocity) or peak KAMs. An explanation may be that the mechanical characteristics of the task play more importance over the technical characteristics, which partly explains the high contributions that velocity and kinetic variables had to both PTs and peak KAMs. This would point towards the physical condition of the participants being the key factor when assessing COD ability, and that possibly, for well-trained athletes, such as recruited in this present study, the importance of technique development may play a subordinate role to developing the overall physical capacity to tolerate the demands of COD. More comprehensive investigations (i.e., kinetic and kinematic analyses) into the differences between ‘stronger’ and ‘weaker’ athletes should be considered to determine whether this is the case.

Although this present study provides more insight into the kinetic and kinematic determinants of cutting from both performance and injury risk standpoints, there are still certain limitations that need to be addressed before more clarity on the topic is accomplished. For example, it was beyond the scope of this current investigation to examine preparatory trunk characteristics, given that our rationale was to develop on previous work (10,25,26) that has focused purely on the braking characteristics in the PFC. How much ‘pre-rotation’ occurs during the PFC is an area that needs to be further explored to provide more clarity on the role of the steps preceding FFC and may further elucidate the ‘multi-step’ nature of COD actions. Another limitation is that trials were limited to performing the cutting maneuver on the right limb (push-off) due to the lab configuration. That being said, it has been shown that only subtle differences in COD biomechanics exist between limbs (13) and so it is argued that informed conclusions for both limbs can still be made from these findings.

PRACTICAL APPLICATIONS

In light of these current findings, it must be acknowledged that cutting programs that emphasize instruction to improve performance come with the inherent risk of increased knee joint loading of cuts from 70-90° cut. The fundamental issue here is that athletes that are driven by peak performance are unlikely to adhere to injury risk mitigation strategies that may compromise their ability to execute movements to the highest level. Therefore, we recommend that practitioners are advised to program accordingly, with a primary aim being to improve the lower-body strength capacity of the athlete (i.e., concentric, eccentric, isometric, reactive) and develop the ability to apply these qualities impulsively over short GCT’s (i.e., rate of force development). The technique cues that have been proven to reduce knee joint loading may be beneficial for athletes that do not display adequate strength levels, and can be subsequently reviewed once they are sufficient. An example here could be that coaching a large LLP may in fact be beneficial for an athlete who can tolerate the increased knee joint loading; however, an individual who demonstrates strength deficits may benefit more from targeted strength training, from which they are coached to express these developing qualities within ‘lower risk’ postures (i.e., reduced LLP). This suggestion may enable practitioners and athletes to optimize the ‘performance-injury risk’ trade-off within the context of the individual’s needs. Coaches and practitioners should also be aware of the role of the PFC during turns of sharper angles and of higher approach velocities and deliver cues according to how sharp the cutting task at hand may be. These recommendations should facilitate the coaching of joint positions and moments that are advantageous to performance to be reinforced, without any concurrent movement breakdown of the athlete through inadequate physical capacity.

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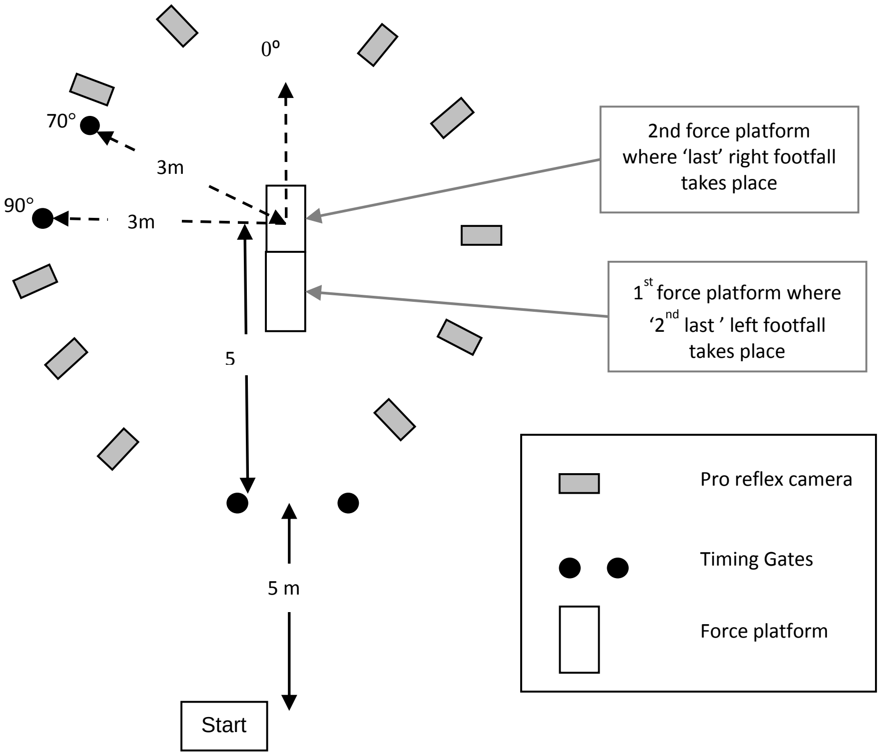

Figure 1. Plan visualization of experimental set-up.

Table 1. Biomechanical variables of interest with definitions.

Variable	Abbreviation	Definition
Independent Variables		
Performance time (s)	-	Time to complete cutting task
Peak external knee abduction moment (Nm·kg^{-1})	Peak KAM	Peak KAM (+ abduction/- adduction) during weight acceptance phase of FFC using inverse dynamics
Peak external knee rotation moment (Nm·kg^{-1})	Peak KRM	Peak KRM during weight acceptance phase of FFC using inverse dynamics
Peak external knee flexion moment (Nm·kg^{-1})	Peak KFM	Peak KFM during weight acceptance phase of FFC using inverse dynamics
Dependent Variables		
Performance Characteristics		
Horizontal approach velocity (m·s^{-1})	-	Model COM position was determined from 10 frames prior to PFC to 10 frames from the toe-off of the FFC. The first derivative of the model COM position was computed to derive anterior-posterior (x), vertical (z) and medial-lateral (y) velocity over this period. Resultant horizontal plane velocity (√ ((COM vel (x)^2) + (COM vel (y)^2)) was subsequently calculated to provide a 'velocity

		profile' along the path of the subject's COM during the cutting maneuver. Resultant horizontal plane velocity at the start of PFC was determined to represent the horizontal approach velocity of the participant for that trial	
Horizontal exit velocity (m·s^{-1})	-	Resultant horizontal plane velocity at take-off of the final foot contact	
Kinetic Characteristics		***Peak***	***Average***
Penultimate horizontal ground reaction force (N·kg^{-1})	hGRF PFC	Normalized peak hGRF during weight acceptance phase of PFC	Normalized average hGRF during weight acceptance phase of PFC
Final horizontal ground reaction force (N·kg^{-1})	hGRF FFC	Normalized peak hGRF during weight acceptance phase of FFC	Normalized average hGRF during weight acceptance phase of FFC
Penultimate vertical ground reaction force (N·kg^{-1})	vGRF PFC	Normalized peak vGRF during weight acceptance phase of PFC	Normalized average vGRF during weight acceptance phase of PFC
Final vertical ground reaction force (N·kg^{-1})	vGRF FFC	Normalized peak vGRF during weight acceptance phase of FFC	Normalized average vGRF during weight acceptance phase of FFC
Final medial-lateral	ML GRF FFC	Normalized peak ML	Normalized average ML

propulsive force (N·kg^{-1})		GRF during propulsion phase of FFC	GRF during propulsion phase of FFC
Horizontal braking force ratio	HBFR	Peak hGRF FFC divided by peak hGRF PFC	Average hGRF FFC divided by peak hGRF PFC
Penultimate ground contact time (s)	PFC GCT	The instant after ground contact of PFC in which the vGRF was higher than 20 N and the point where the vGRF subsided past 20 N (end of contact)	
Final ground contact time (s)	FFC GCT	The instant after ground contact of FFC in which the vGRF was higher than 20 N and the point where the vGRF subsided past 20 N (end of contact)	
Peak sagittal plane hip, knee and ankle moments (Nm·kg^{-1})	-	Peak external joint moments during weight acceptance and propulsion phase of FFC using inverse dynamics	
Kinematic Characteristics			
Peak hip, knee and ankle joint flexion angles (°)	-	Derived from the following order of rotations: flexion (+)	
Right knee adduction angle (°)	KAA	Maximum knee adduction angle (-) during weight acceptance phase of FFC	
Lateral leg plant distance	LLP	Lateral distance from COM of the plant foot at	

(m)		initial foot contact of foot to proximal end of the pelvis (relative to the frontal plane)
Lateral trunk flexion angle (°)	-	Angle of the trunk in the frontal plane relative to a vertical line in the lab co-ordinate system: upright (0)/trunk flexion away from plant leg (+)/trunk flexion towards plant leg (-)
Initial foot progression angle (°)	-	Angle of foot progression relative to original direction: straight (0)/inward rotation (+)/outward rotation (-)
'True' cut angle (°)	-	Actual angle of cut that was performed during the intended 70-90° COD task. Calculated using the following: tan (y velocity component at take-off/ x velocity component at take-off)

Key: COM = center of mass; COD = change of direction.

Table 2

Table 2. Descriptive statistics and correlation values for variables with large and moderate associations with performance time and multi-planar knee joint loading.

	Mean ± SD	**R or ρ**	**P**
Performance time (s) #	2.07 ± 0.13	-	-
Peak KAM (Nm·kg^{-1})	1.04 ± 0.73	- 0.590	<0.001
Horizontal approach velocity (m·s^{-1})	4.29 ± 0.31	- 0.579	<0.001
Peak KRM (Nm·kg^{-1})	-0.76 ± 0.36	0.525	0.001
Peak KFM (Nm·kg^{-1})	2.96 ± 0.72	- 0.509	0.002
Horizontal exit velocity (m·s^{-1})	3.30 ± 0.25	-0.451	0.007
Peak hip flexor moment FFC (Nm·kg^{-1})	- 3.50 ± 1.77	0.418	0.014
Peak knee abduction moment (Nm·kg^{-1}) #	1.04 ± 0.73	-	-
Peak hip flexor moment FFC (Nm·kg^{-1})	- 3.50 ± 1.77	-0.624	<0.001
Performance time (s)	2.07 ± 0.13	-0.590	<0.001
Peak KFM (Nm·kg^{-1})	2.96 ± 0.72	0.549	0.002
Peak KRM (Nm·kg^{-1})	-0.76 ± 0.36	-0.488	0.003
Horizontal approach velocity (m·s^{-1})	4.29 0.31	0.414	0.015
Peak knee rotation moment (Nm·kg^{-1})	-0.76 ± 0.36	-	-
Average ML FFC (N·kg^{-1})	0.66 ± 0.17	-0.638	<0.001
Average hGRF FFC (N·kg^{-1})	-0.81 ± 0.17	0.581	<0.001
Peak hGRF FFC (N·kg^{-1})	-1.38 ± 0.33	0.576	<0.001
Horizontal approach velocity (m·s^{-1})	4.29 0.31	-0.568	<0.001
Performance time (s) #	2.07 ± 0.13	0.525	0.001
Peak hip flexor moment FFC (Nm·kg^{-1}) #	-3.50 ± 1.77	0.517	0.002
Peak KFM (Nm·kg^{-1})	2.96 ± 0.72	-0.494	0.003
Peak KAM (Nm·kg^{-1})	1.04 ± 0.73	-0.488	0.003
Peak ML FFC (N·kg^{-1})	1.18 ± 0.33	-0.430	0.011
Peak vGRF FFC (N·kg^{-1})	-1.39 ± 0.40	-0.412	0.016
Peak knee flexion moment (Nm·kg^{-1})	2.96 ± 0.72	-	-

Peak KAM (Nm·kg^{-1})	2.96 ± 0.72	- 0.549	0.002
Performance time (s)	2.96 ± 0.72	- 0.509	0.002
Peak KRM (Nm·kg^{-1})	-0.76 ± 0.36	-0.494	0.003

Key: # = Spearman’s correlation coefficient; SD = standard deviation; FFC = final foot contact; KAM = knee abduction moment; KRM = knee rotation moment; KFM = knee flexion moment; ML = medial-lateral.

Table 3. Descriptive statistics and Pearson's correlation for variables large and moderate associations with exit velocity and approach velocity.

	Mean ± SD	**R or ρ**	**P**
Horizontal exit velocity ($m{\cdot}s^{-1}$)	3.30 ± 0.25	-	-
GCT FFC (s)	0.31 ± 0.05	- 0.590	<0.001
Lateral leg plant distance (m)	- 0.31 ± 0.05	- 0.582	0.001
Peak ML propulsive force ($N{\cdot}kg^{-1}$)	1.18 ± 0.33	0.570	<0.001
Horizontal approach velocity ($m{\cdot}s^{-1}$)	4.29 ± 0.31	0.562	0.001
Average ML propulsive force ($N{\cdot}kg^{-1}$)	0.66 ± 0.17	0.512	0.002
Horizontal approach velocity ($m{\cdot}s^{-1}$)	4.29 ± 0.31	-	-
Average hGRF FFC ($N{\cdot}kg^{-1}$)	- 0.81 ± 0.17	- 0.622	<0.001
Peak KAM ($Nm{\cdot}kg^{-1}$) #	1.04 ± 0.73	- 0.590	<0.001
Peak KRM ($Nm{\cdot}kg^{-1}$)	2.96 ± 0.72	-0.568	<0.001
Peak hGRF PFC ($N{\cdot}kg^{-1}$)	- 1.39 ± 0.40	- 0.548	0.001
Peak ML propulsive force ($N{\cdot}kg^{-1}$)	1.18 ± 0.33	0.520	0.002
Peak hip extensor moment FFC ($Nm{\cdot}kg^{-1}$) #	- 3.50 ± 1.77	0.511	0.002
Peak hGRF force FFC ($N{\cdot}kg^{-1}$)	- 1.38 ± 0.33	- 0.492	0.003
Average hGRF force PFC ($N{\cdot}kg^{-1}$)	- 0.54 ± 0.09	- 0.478	0.004
Peak vGRF PFC ($N{\cdot}kg^{-1}$) #	2.54 ± 0.56	0.423	0.013

Key: # = Spearman's correlation coefficient; SD = standard deviation; ML = medial-lateral; FFC = final foot contact; KAM = knee abduction moment; KRM = knee rotation moment; PFC = penultimate foot contact; vGRF = vertical ground reaction force; hGRF = horizontal ground reaction force.

Table 4

Table 4. Performance characteristic comparisons between fast and slow performers.

Variable	**Fast (n = 10)**	**Slow (n = 10)**	**P-value**	***d***	**CI (95%)**		**Descriptor**
Performance variable					*LB*	*UB*	
Performance time (s) #	1.95 ± 0.06	2.20 ± 0.10	<0.001	- 3.0	- 1.7	- 4.4	Very large
Horizonal approach velocity (m·s^{-1})	4.58 ± 0.20	4.08 ± 0.28	<0.001	2.0	1.0	3.1	Very large
Horizontal exit velocity (m·s^{-1})	3.48 ± 0.17	3.20 ± 0.28	0.014	1.2	0.3	2.2	Large

Key: # = Kruskal–Wallis H test; *d* = Cohen's *d* effect size; CI = 95% confidence interval; LB = lower bound 95% confidence interval; UB = upper bound 95% confidence interval.

Table 5. Kinetic characteristic comparisons between fast and slow performers.

Variable	**Fast (n = 10)**	**Slow (n = 10)**	**P-value**	***d***	**CI (95%)**		**Descriptor**
GRF Properties					*LB*	*UB*	
Peak vGRF PFC (N·kg^{-1})	2.72 ± 0.61	2.41 ± 0.54	0.248	0.5	- 0.4	1.4	Small
Peak hGRF PFC (N·kg^{-1})	- 1.57 ± 0.39	- 1.24 ± 0.45	0.097	-0.8	- 1.7	0.1	Moderate
Average hGRF PFC (N·kg^{-1})	-0.57 ± 0.072	- 0.49 ± 0.10	0.050	-0.9	- 1.9	0.0	Moderate
Peak vGRF FFC (N·kg^{-1})	2.65 ± 0.42	2.54 ± 0.530	0.616	0.2	- 0.7	1.1	Small
Peak hGRF FFC (N·kg^{-1})	- 1.47 ± 0.29	- 1.28 ± 0.22	0.127	-0.7	- 1.6	0.2	Moderate
Average hGRF FFC (N·kg^{-1})	- 0.90 ± 0.16	- 0.78 ± 0.15	0.087	-0.8	- 1.7	0.1	Moderate
Peak HBFR	1.10 ± 0.29	1.01 ± 0.44	0.595	0.2	- 0.6	1.1	Small
Average HBFR #	1.60 ± 0.30	1.68 ± 0.67	0.705	-0.2	- 1.0	0.7	Small
Peak ML propulsive force FFC (N·kg^{-1})	1.32 ± 0.32	1.11 ± 0.35	0.176	0.6	- 0.3	1.5	Moderate
Average ML propulsive force FFC (N·kg^{-1})	0.71 ± 0.18	0.65 ± 0.17	0.481	0.3	- 0.6	1.2	Small
GCT PFC (s)	0.19 ± 0.03	0.20 ± 0.04	0.357	- 0.4	- 0.5	- 0.2	Small
GCT FFC (s)	0.29 ± 0.04	0.33 ± 0.06	0.123	- 0.7	- 0.6	- 0.1	Moderate
Moments							
Peak KAM (Nm·kg^{-1}) #	1.62 ± 1.14	0.70 ± 0.18	0.005	1.1	0.2	2.1	Moderate
Peak KRM (Nm·kg^{-1}) #	-1.01 ± 0.34	-0.54 ± 0.18	0.005	-1.7	- 2.7	- 0.7	Large
Peak right hip flexor moment (Nm·kg^{-1}) #	- 4.44 ± 2.35	- 2.77 ± 0.95	0.016	- 0.9	- 1.8	0.0	Moderate
Peak KFM (Nm·kg^{-1})	3.46 ± 0.72	2.68 ± 0.75	0.029	1.1	0.1	2.0	Moderate
Peak right ankle dorsi-flexor moment (Nm·kg^{-1})	- 1.53 ± 0.82	- 1.37 ± 0.50	0.624	- 0.2	- 1.1	0.7	Small
Peak left hip flexor moment (Nm·kg^{-1}) #	1.76 ± 0.62	3.21 ± 4.15	0.326	- 0.5	- 1.4	0.4	Small
Peak left knee flexor moment (Nm·kg^{-1}) #	3.26 ± 0.60	3.17 ± 1.53	0.257	0.1	- 0.8	1.0	Trivial
Peak left ankle dorsi-flexor moment (Nm·kg^{-1}) #	- 0.66 ± 0.15	- 0.80 ± 0.42	0.545	0.4	- 0.4	1.3	Small

Key: # = Kruskal–Wallis H test; *d* = Cohen’s *d* effect size; CI = 95% confidence interval; GRF = ground reaction force; LB = lower bound 95% confidence interval; UB = upper bound 95% confidence interval; vGRF = vertical ground reaction force; PFC = penultimate foot contact; hGRF = horizontal ground reaction force; FFC = final foot contact; HBFR = horizontal braking force ratio; ML = medial-lateral; GCT = ground contact time; KAM = knee abduction moment; KRM = knee rotation moment; KFM = knee flexion moment.

Table 6

Table 6. Kinematic characteristic comparisons between fast and slow performers.

Variable	**Fast (n = 10)**	**Slow (n = 10)**	**P-value**	***d***	**CI (95%)**		**Descriptor**
Technique					*LB*	*UB*	
Peak KAA (°)	- 12.08 ± 5.54	- 6.94 ± 4.96	0.042	- 1.0	- 1.9	- 0.1	Moderate
LLP distance (m)	- 0.34 ± 0.07	- 0.31 ± 0.05	0.302	-0.5	- 1.4	0.4	Small
Lateral trunk flexion angle (°)	- 20.14 ± 4.56	- 21.22 ± 8.55	0.743	0.2	- 0.7	1.0	Small
Initial foot progression angle (°) #	8.36 ± 34.96	14.09 ± 4.69	0.895	-0.2	- 1.1	0.6	Small

Key: # = Kruskal–Wallis H test *d* = Cohen's *d* effect size; CI = 95% confidence interval; LB = lower bound 95% confidence interval; UB = upper bound 95% confidence interval; KAM = knee adduction moment; KAA = knee adduction angle; LLP = lateral leg plant. All reported values are with respect to final foot contact.