Effect of Asymmetry on Biomechanical Characteristics During 180° Change of Direction

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Abstract

Thomas, C, Dos'Santos, T, Comfort, P, and Jones, PA. Effect of asymmetry on biomechanical characteristics during 180° change of direction. *J Strength Cond Res* XX(X): 000–000, 2020—The aim of this study was to explore the effect of asymmetry on biomechanical characteristics during two 180° change of direction (CoD) tasks (505 and modified 505 [505_{mod}]). Fifty-two male (n = 24; age = 22.1 ± 4.8 years; height = 1.78 ± 0.06 m; body mass = 76.9 ± 10.8 kg) and female (n = 28; age = 19.1 ± 1.7 years; height = 1.67 ± 0.06 m; body mass = 60.4 ± 7.4 kg) team-sport players were recruited for this investigation. Three-dimensional motion data using 10 Qualisys Oqus 7 infrared cameras (240 Hz) and ground reaction force (GRF) data from 2 AMTI force platforms (1,200 Hz) were collected to analyze penultimate contacts (PEN) and final foot contacts. A series of repeated-measures analysis of variance were used to examine for differences in each dependent variable. Significant differences existed between dominant (D) and nondominant (ND) limbs for knee abduction angle (KAA) during 505_{mod} (p = 0.048), while significant differences existed for peak horizontal and vertical GRF (vGRF) ($p < 0.001$) during 505. For both tasks, the PEN involved significantly greater peak vGRF, hip flexion angles, hip extensor moments, knee flexion angles, and knee extensor moments, but lower average vGRF, horizontal GRF, and peak ankle extensor moments. For 505, the ND limb involved significantly greater peak vGRF, but the opposite was revealed for peak horizontal GRF. For 505_{mod}, the D limb involved significantly greater KAAs. Finally, there was a significant interaction (group × limb) for peak horizontal GRF ratio during 505. For both tasks, there was no interaction or main effects for time to completion. Therefore, it appears asymmetry influences GRFs and KAAs, but not completion time during 180° CoD in team-sport players.

Key Words: hop testing, pivoting, anterior cruciate ligament injury, deceleration, ground reaction forces, knee abduction moments

Introduction

It has previously been observed that female players accrue higher rates of noncontact anterior cruciate ligament (ACL) injuries compared with male players (48). There is also evidence that sex plays a crucial role in knee joint mechanics during change of direction (CoD) tasks (cutting and pivoting), which is believed to contribute to increased risk of ACL injury (7,44,52). Thus far, several studies have shown that greater knee abduction angles (KAAs) (41,45), knee abduction moments (KAMs) (43,45,51,52), ground reaction forces (GRFs) (58), and smaller knee flexion angles (41,45,58) are observed during cutting and pivoting. Moreover, video analysis studies have revealed postures at initial contact (IC) such as a dorsiflexed ankle (6), abducted hip (49), extended knee joint (6,39,49), and laterally flexed and rotated torso (53) to be associated with ACL injuries during CoD. Similarly, laboratory studies have found these lower-limb postures to increase KAM (15,32,34), which could lead to increased ACL strain (46) and subsequent injury (30). However, far too little attention has been paid to the influence of asymmetries on biomechanical characteristics during CoD and the potential for noncontact ACL injury, specifically in team-sport players.

Change of direction (side-stepping, crossover cuts, and pivots) are highly important in team sports and are often linked to decisive moments such as evading opponents or creating space to promote attacking opportunities (20,22). Jones and Bampouras (31) provided a definition of CoD as the ability to decelerate, reverse, or change movement direction and accelerate again and is considered preplanned. It has been previously observed that up to 70% of noncontact ACL injuries occur during a cutting or CoD maneuver (4,5). Previous research (7) suggests that limb dominance (kicking vs. support limb) plays a role in ACL injury, specifically in soccer players. Although noncontact ACL injuries were evenly distributed (kicking limb = 30 subjects; support limb = 28 subjects), 74% (20 out of 27 subjects) of male subjects suffered a noncontact ACL injury on the kicking limb, compared with 32% (10 out of 31 subjects) of female subjects.

With the exception of a few (8,9,26), most research on asymmetries have been performed in relation to CoD speed (time to completion) (11,19,31,36,40,42), with data suggesting asymmetry to have no adverse effect on performance. Yet, studies of asymmetries show subtle differences in knee joint mechanics during weight acceptance (WA) between preferred and nonpreferred limbs (9). By contrast, 20 collegiate female soccer players were found to exhibit similar movement patterns between dominant (kicking) and nondominant limbs (26). However, current methods of categorizing asymmetry are shown to be questionable, whereby subjects who perceive a limb to be "dominant" may not truly be "dominant" based on the muscle strength quality being assessed (21). Therefore, it is important for researchers and practitioners to categorize asymmetry appropriately because this would enhance our understanding of asymmetries as an etiological factor for ACL injury risk and provide a sound platform on which to base training interventions.

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Previous research has focused on how body posture affects KAM during the final contacts (FC) when cutting and pivoting (37,38,43). Cortes et al. (12) observed heel-first landings during 180° pivots to produce increased KAM at IC than sidestep cutting. Also, the same authors found an increased positive foot progression angle (angle of foot orientation relative to the original direction of travel (0° straight, positive rotated inward [anti-clockwise], negative rotated outward [clockwise]) during 180° pivots compared with a 45° sidestep cut task (14). Sigward et al. (46) found changes in directions of greater magnitude to result in 2.4 times greater KAM and 4 times greater hip abduction angle, when comparing 110° turns with 45° cuts. Additional findings revealed greater sex differences in KAM during 110° turns, but no differences were observed in 45° cuts. Taken together, these findings may suggest that the mechanics related to optimal performance may differ depending on the magnitude of the change in direction and potentially indicate female players are at a greater risk of injury when performing sharper changes in direction. Increased attention (18,25,32,34,35) is being directed toward the role of the penultimate contacts (PEN) during changes in direction, and how body postures and load distribution affect KAM during sharper changes in direction. Efficient deceleration requires the application of high forces in the shortest time possible to decrease the body's momentum to reposition the body in the desired direction. It has been suggested that lowering GRF during the FC (plant foot), when the lower limb is in a posture that evokes high KAM through increasing the amount of braking performed in the step before the turn (PEN), may help lower knee joint loads during the FC (25). A preliminary study (25) found that the PEN (the second last foot contact with the ground before moving into a new intended direction) before the FC resulted in greater peak vertical GRF (vGRF) and anterior–posterior GRF and internal knee extensor moments compared with FC during a 180° pivot, and that greater peak horizontal braking force at PEN was related to faster turn times. Furthermore, Havens and Sigward (25) found braking demands to be evenly distributed across approach and execution steps during a 45° cut, whereas greater impulse and posterior GRF was required in the approach step during a 90° cut. Theoretically, if the body's momentum can be decreased during the PEN, this may lower KAM experienced during the FC (turn), due to lower resultant GRFs. A recent study (33) observed increased braking forces in the PEN relative to the FC, but no association to peak KAM in 90° cuts. In addition, the same authors revealed similar findings in a follow-up study using 180° pivots (34). Although no direct association to peak KAM was found, further analysis in both studies revealed players with lower peak KAM had a lower FC:PEN peak horizontal GRF ratio (HGRFR). These findings suggest players with lower peak KAM executed cutting and pivoting tasks by increased braking during the PEN. These results reveal the potential importance of the PEN during pivoting to brake early and overcome less momentum during the FC, which may have implications for performance and risk of injury.

As mentioned previously, recent evidence (18,25,32,35) suggests that the PEN may play an important role in CoD speed, yet there have been no studies which compare the interaction between technique characteristics and asymmetries during PEN and FC. It has been suggested that further research should be considered to gather a greater understanding of the influence of asymmetries to optimal technique for injury prevention for both screening and technique training interventions. Therefore, the primary aim of this study was to investigate differences in braking strategy (PEN vs. FC) regarding the categorization of asymmetry during 180° CoD in team-sport players. The secondary aim was to investigate differences in kinematics (lower-limb joint angles) and kinetics (GRFs and moments) between dominant (D) and nondominant (ND) limbs during 180° CoD. Finally, this study aimed to explore kinematic and kinetic differences between PEN and FC of 180° CoD. It was hypothesized that subjects with greater asymmetry would demonstrate altered CoD biomechanics compared with subjects of lesser asymmetry. It was also hypothesized that subjects would exhibit greater KAA and KAM when turning off the ND limb, compared with the D limb. Furthermore, it was hypothesized that subjects would demonstrate a different braking strategy (PEN vs. FC) when turning off the ND limb, compared with the D limb.

Methods

Experimental Approach to the Problem

A cross-sectional study design was used to evaluate biomechanical characteristics during a 180° CoD maneuver using 3D-motion analysis and GRF analysis. Subjects were grouped based on single-leg hop asymmetry, and thereafter, repeated-measures analysis of variance (ANOVA) was used to examine for differences in biomechanical (kinematics [lower-limb joint angles] and kinetics [GRFs and moments]) and performance variables (completion time and CoD deficit). Testing took place on an indoor synthetic running surface (Mondo, SportsFlex, 10 mm; Mondo America, Inc., Mondo, Summit, NJ). Each player was required to attend the laboratory on 2 separate occasions. The first occasion was a familiarization session on the protocol used in the study with data collected on the subsequent session. All subjects performed a test of asymmetry (single-leg hop) and 2 CoD tasks (505 and modified 505 [505_{mod}]).

Subjects

This study included 52 male (n = 24; age = 22.0 ± 4.3 years; height = 1.78 ± 0.06 m; body mass = 76.9 ± 10.8 kg) and female (n = 28; age = 19.4 ± 2.7 years; height = 1.67 ± 0.06 m; body mass = 60.4 ± 7.4 kg) team-sport players. Specifically, male subjects participated in soccer (n = 12; age = 22.0 ± 4.3 years; height = 1.79 ± 0.5 m; body mass = 75.0 ± 7.4 kg) and cricket (n = 12; age = 21.9 ± 4.5 years; height = 1.76 ± 0.06 m; body mass = 78.2 ± 12.0 kg), whereas female subjects participated in soccer (n = 12; age = 21.1 ± 2.1 years; height = 1.68 ± 0.07 m; body mass = 56.2 ± 6.2 kg) and netball (n = 16; age = 17.8 ± 2.3 years; height = 1.74 ± 0.06 m; body mass = 63.2 ± 5.7 kg). Subject characteristics were measured mean ± *SD*. At the time of testing, subjects were performing 4–5 sport-specific sessions, plus 3 resistance training sessions per week. All subjects had >8 years competitive experience and >3 years resistance training experience. All subjects met the inclusion criteria: (a) team-sport players, (b) considered to be high-standard (collegiate, semi-professional), (c) did not suffer from an ACL injury, and (d) did not suffer from any other lower-limb injury within the last 6 months. Each player was in the preseason phase of training during his or her participation in this study. All subjects read and signed a written informed consent form before participation, with consent from the parent or guardian of all subjects under the age of 18. Approval for the study was provided by the University of Salford ethics committee.

Procedures

Single-Leg Hop. The single-leg hop was used as a measure of unilateral horizontal jump performance. A 6-m-long, 15-cm-wide line was marked on the floor, along the middle of which was a standard tape measure, perpendicular to the starting line. The test began with subjects placing the toes on the back of the start line, before balancing on the leg to be tested, with the hands on the hips. Subjects were instructed to use a countermovement, and no restrictions were placed on body angles attained during the preparatory phase, with the instruction to hop as far forward as possible, taking off from one leg, before landing on the same leg. Subjects had to "stick" the landing for 2 seconds, with no movement of the foot or hands touching the ground, for the trial to be counted. If the subject did not do this, the trial was discarded, and another was attempted. The distance was measured to the nearest 0.01 m using a standard tape measure, perpendicular from the front of the start line to the posterior aspect of the back heel at the landing. Subjects performed a minimum of 3 warm-up trials on each limb (47), followed by 3 hops for maximal horizontal distance. The order of limb was randomized and counterbalanced between subjects. The mean hop distance for the 3 trials for each limb was used for further analysis. Limb dominance was defined as the limb that produced the furthest single-leg hop distance. Asymmetry for dominant and nondominant limbs was calculated by the formulas (dominant limb − nondominant limb)/dominant limb × 100.

Change of Direction Speed. Change of direction speed was assessed using 505, followed by 505_{mod} tests on a third-generation artificial rubber crumb surface (Mondo, Sports-Flex, 10 mm; Mondo America, Inc., Mondo). For both tests, subjects performed 3 trials on each leg, in a randomized order, with a 2-minute rest between trials. Subjects started 0.5 m behind the photocell gates, to prevent any early triggering of the initial start gate, from a 2-point staggered start. Timing gates were again placed at the approximate hip height for all subjects. For the 505, subjects were instructed to sprint to a line marked 15 m from the start line, placing either left or right foot on the line, depending on the trial, turn 180°, and sprint back 5 m through the finish (23). For 505_{mod} testing, subjects were instructed to sprint to a line marked 5 m from the start line, placing either left or right foot on the line, depending on the trial, turn 180°, and sprint back 5 m through the finish (23). During both 505 and 505_{mod}, if the subject changed direction before hitting the turning line, or turned off the incorrect foot, the trial was disregarded, and the subject completed another trial after the rest period. The mean performance from each of the 3 trials, for both 505 and 505_{mod}, was used for further analysis.

For both tasks, all subjects performed a minimum of 6 trials of on each limb (D and ND) in a randomized order and were counterbalanced between subjects. Subjects were instructed to perform trials at maximum speed while contacting the central portion of the second platform during FC to ensure a homogeneous distance of travel between trials and without previous stuttering or prematurely turning before FC. Verbal feedback was provided to rectify any of the abovementioned aspects on subsequent trials. Total time to complete the tasks was measured using a set of Brower timing lights (Brower Timing Systems, Draper, UT) set at approximate hip height for all subjects as previously recommended (57) to ensure that only one body part, such as the lower torso, breaks the beam. Subjects started 0.5 m behind the first gate, to prevent any early triggering of the initial start gate, from a 2-point staggered start. Yet, some flexibility was allowed for the exact starting point for each subject to allow for the subjects differing stride pattern as they approached the 2 force platforms. Each subject was allowed time before data collection to identify their exact starting point to ensure an appropriate force platform contact. The fastest 3 trials were used for further analysis and averaged across these 3 trials.

Data Collection. All subjects were fitted with identical size-appropriate compression tops (Champion Vapor; Champion, Winston-Salem, NC) and wore the same indoor shoes (Balance W490; New Balance, Boston, MA). All subjects performed 505 and 505_{mod} CoD tasks, turning off the D and ND limbs. The 505 and 505_{mod} involved running toward 2 force platforms, whereby the first force platform was used to measure GRFs from the PEN foot contact, whereas the second force platform was used to measure GRFs from the FC.

In line with previous research (32), reflective markers were placed on the following body landmarks: mid-clavicle; seventh cervical vertebrae, right and left; shoulder; iliac crest; anterior superior iliac spine; posterior superior iliac spine; greater trochanter; medial epicondyle; lateral epicondyle; lateral malleouli; medial malleouli; heel; fifth, second, and first metatarsal heads using double-sided adhesive tape. Subjects also wore a 4 marker "cluster set" (4 retroreflective markers attached to a light-weight rigid plastic shell) on the trunk, right and left; thigh; and shin, to approximate motion of these segments during dynamic trials. The use of clusters is suggested to be more accurate and practical for tracking motion than individual skin markers (2), with 4 markers suggested as optimal (10). The thigh and shank cluster sets were attached using Velcro elasticated wraps, whereas a compression top (Champion Vapor; Champion) was used to attach the trunk cluster set.

Three-dimensional motions of these markers were collected while performing each athletic task using Qualisys "Pro reflex" (Model number: MCU 240, Gothenburg, Sweden) infrared cameras (240 Hz) operating through Qualisys Track Manager software (C-motion, version 3.90.21, Gothenburg, Sweden). Ground reaction forces were collected from 2 600 × 900 mm AMTI (Advanced Mechanical Technology, Inc., Watertown, MA) force platforms (Model number: 600900) embedded into the running track sampling at 1,200 Hz.

Data Analysis. From a standing trial, a lower extremity and trunk 6 degrees of freedom kinematic model was created for each subject, including the pelvis, thigh, shank, and foot using Visual 3D software (C-motion, version 3.90.21). This kinematic model was to quantify the motion at the hip, knee, and ankle joints using a Cardan angle sequence x–y–z (27). The local coordinate system was defined at the proximal joint center for each segment. The static trial position was designated as the subject's neutral (anatomical zero) alignment, and subsequent kinematic measures were related back to this position. Segmental inertial characteristics were estimated for each subject (17). The model used a CODA pelvis orientation (Charnwood Dynamics Ltd., Leicestershire, UK). The knee and ankle joint centers were defined as the midpoint of the line between lateral and medial markers. Lower-limb joint moments were calculated using an inverse dynamics approach (56) through Visual 3D software (C-motion, version 3.90.21). Joint moments are defined as external moments. The trials were time normalized for each subject, with respect to the ground contact time of the CoD task. Initial contact was defined as the instant after-ground contact that the vGRF was higher than 20 N, and end of contact was defined as the point where the vGRF subsided past 20 N for both PEN and FC. The WA phase of ground contact was defined as from the instant of IC (vGRF >20 N) to the point of maximum knee flexion during ground contact as used previously (28,32,35). Joint coordinate and force data were smoothed in visual 3D with a Butterworth low-pass digital filter with cutoff frequencies of 12 and 25 Hz, respectively. Cutoff frequencies were selected based on a residual analysis (56) and visual inspection of the data.

For comparisons between PEN and FC, peak (PK) and average (AVE) vertical (Fz) and horizontal (Fx) GRFs were determined along with PK hip, knee, and ankle dorsiflexion angles and PK hip, knee, and ankle moments in the sagittal plane during the WA phase and analyzed in Microsoft Excel (version 2016; Microsoft Corp., Redmond, WA). Furthermore, PK KAA and KAM were calculated during the FC. Joint moment data were normalized to body mass ($Nm \cdot kg^{-1}$). To evaluate deceleration strategy from PEN to FC, a FC/PEN contact horizontal (Fx component) HGRFR was also calculated (32).

Statistical Analyses

Data are presented as mean ± *SD*. In line with previous research (1,24), subjects were classified into balanced or asymmetrical for the single-leg hop based on the mean + (1 *SD*) of the asymmetry. Subjects were grouped based on asymmetry accordingly: low group (LG; $n = 33$; ≤mean asymmetry), moderate group (MG; $n = 10$; mean asymmetry-to-1 *SD*), and high group (HG; $n = 9$; ≥ asymmetry + 1 *SD*). Normality of data was assessed by Shapiro–Wilk's statistic, whereas homogeneity of variances was examined using Levene's test. A 2 × 2 × 3 (limb × contact × group) repeated-measures ANOVA was used to examine for differences in each dependent variable in the sagittal plane. A 2 × 3 (limb × group) repeated-measures ANOVA was used to compare differences in completion time, HGRFR, KAA, and KAM. Partial eta-square (η_p^2) was used for effect size and interpreted with the following scale: 0.01 (small), 0.06 (medium), and 0.15 (large) (12). A series of one-way ANOVA were used to examine the differences in body mass and asymmetries between each group. Where significant differences were found, Bonferroni post hoc analyses were completed to detect differences between groups. The magnitude of differences in asymmetries between groups was also expressed as standardized mean difference using the Hedges' *g* method (29) and interpreted accordingly (12). All statistical analyses were performed in SPSS for Windows (version 23; IBM, New York, NY), and the criterion for statistical significance was set at $p \leq 0.05$.

Results

For physical characteristics, no statistically significant differences ($p > 0.05$; $d = 0.23–0.45$) in body mass existed between groups. Statistically significant differences in asymmetries existed among groups. The single-leg hop asymmetry ratios of the HG (10.0%) were statistically greater than those of both the LG (2.0%; $p < 0.001$; $g = 5.08$) and MG (5.5% $p < 0.001$; $g = 2.35$). The asymmetry ratios of the MG were statistically greater ($p < 0.001$; $g = 2.91$) than those of the LG (Tables 1–3).

505

For AVE vGRF, there were no interactions, and there were no main effects for group or limb. However, there was a main effect for contact ($p < 0.001$), in which FC were greater than PEN. For PK vGRF, there were no interactions, and there were no main effects for group or contact. However, there was a main effect for limb ($p < 0.001$), in which ND limbs were greater than D limbs. For AVE HGRF, there were no interactions, and there were no main effects for group or limb. However, there was a main effect for contact, in which FC were greater than the PEN ($p < 0.001$). For PK HGRF, there were no interactions or main effects for group. However, there was a main effect for limb ($p < 0.001$), in which D limbs were greater than ND limbs, and a main effect for contact ($p < 0.001$), in which FC were greater than PEN.

For PK hip flexion angle, there were no interactions, and there were no main effects for group or limb. However, there was a main effect for contact ($p < 0.001$), in which PEN were greater than FC. For PK hip extensor moment, there were no interactions, and there were no main effects for group or limb. However, there was a main effect for contact ($p = 0.003$), in which PEN were greater than FC.

For PK knee flexion angle, there were no interactions, and there were no main effects for group or limb. However, there was a main effect for contact ($p < 0.001$), in which PEN were greater than FC. For PK knee extensor moment, there were no interactions, and there were no main effects for group or limb. However, there was a main effect for contact ($p < 0.001$), in which PEN were greater than FC.

For PK ankle flexion angle, there were no interactions or main effects. For PK ankle extensor moment, there were no interactions, and there were no main effects for group or limb. However, there was a main effect for contact ($p = 0.000$), in which FC were greater than PEN.

For 505 completion time, there was no interaction or main effects. For AVE HGRFR, there was no interaction or main effects. For PK HGRFR, there were no main effects for group or limb. However, there was an interaction for group × limb ($p < 0.001$). For KAA, there was no interaction or main effects. For KAM, there was no interaction or main effects (Table 4).

Modified 505

For AVE vGRF, there were no interactions, and there were no main effects for group or limb. However, there was a main effect for contact ($p < 0.001$), in which FC were greater than PEN. Similarly, PK vGRF revealed no interactions, and there were no main effects for group or limb. However, there was a main effect for contact ($p < 0.001$), in which PEN were greater than FC. For AVE HGRF, there were no interactions, and there were no main effects for group or limb. However, there was a main effect for contact, in which FC were greater than the PEN ($p < 0.001$). For PK HGRF, there were no interactions or main effects.

For PK hip flexion angle, there were no interactions, and there were no main effects for group or limb. However, there was a main effect for contact ($p < 0.001$), in which PEN were greater than FC. For PK hip extensor moment, there were no interactions, and there were no main effects for group or limb. However, there was a main effect for contact ($p = 0.039$), in which PEN were greater than FC.

For PK knee flexion angle, there were no interactions, and there were no main effects for group or limb. However, there was a main effect for contact ($p < 0.001$), in which PEN were greater

Table 1

Mean ± *SD* of force–time characteristics, joint angles, and moment characteristics between the weight acceptance phase of PEN and final contacts for the 505.*

Variable	LG				MG				HG			
	Penultimate contact		Final contact		Penultimate contact		Final contact		Penultimate contact		Final contact	
	D	ND	D	ND	D	ND	D	ND	D	ND	D	ND
	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*
Force–time characteristics												
AVE vGRF (BM)	0.8 ± 0.2	0.8 ± 0.2	1.3 ± 0.2	1.3 ± 0.2	0.9 ± 0.2	0.8 ± 0.3	1.3 ± 0.2	1.3 ± 0.2	0.9 ± 0.3	0.9 ± 0.2	1.4 ± 0.1	1.3 ± 0.2
PK vGRF (BM)	2.4 ± 0.8	2.3 ± 0.6	1.9 ± 0.4	1.9 ± 0.4	2.6 ± 0.6	2.2 ± 0.6	1.9 ± 0.4	1.8 ± 0.4	2.2 ± 0.7	2.4 ± 1.0	1.9 ± 0.3	1.8 ± 0.3
AVE HGRF (BM)	0.5 ± 0.2	0.5 ± 0.1	1.0 ± 0.2	1.0 ± 0.2	0.5 ± 0.2	0.5 ± 0.2	1.0 ± 0.1	0.9 ± 0.2	0.5 ± 0.2	0.5 ± 0.2	1.0 ± 0.1	1.0 ± 0.1
PK HGRF (BM)	1.7 ± 0.7	1.6 ± 0.5	1.5 ± 0.3	1.5 ± 0.3	1.6 ± 0.5	1.5 ± 0.4	1.4 ± 0.3	1.4 ± 0.4	1.5 ± 0.6	1.7 ± 0.7	1.5 ± 0.2	1.4 ± 0.2
Joint kinematics and kinetics												
PK hip flexion angle (°)	89.5 ± 14.3	91.2 ± 15.2	59.1 ± 14.8	61.8 ± 15.7	87.6 ± 17.4	88.0 ± 13.2	56.6 ± 11.5	60.7 ± 15.7	79.5 ± 16.1	86.7 ± 8.1	52.1 ± 20.6	48.5 ± 13.1
PK hip extensor moment (Nm·kg^{-1})	2.5 ± 0.9	2.6 ± 0.9	2.5 ± 0.7	2.5 ± 1.1	2.9 ± 0.8	2.6 ± 0.7	2.0 ± 0.7	2.1 ± 0.5	2.4 ± 0.8	2.5 ± 1.3	2.0 ± 0.8	2.0 ± 0.8
PK knee flexion angle (°)	113.6 ± 13.8	112.7 ± 15.8	68.3 ± 8.3	68.3 ± 9.8	105.7 ± 19.6	105.6 ± 18.6	67.3 ± 5.4	68.9 ± 13.4	101.8 ± 15.0	106.1 ± 13.4	66.2 ± 11.8	64.3 ± 16.1
PK knee extensor moment (Nm·kg^{-1})	3.4 ± 1.3	3.2 ± 1.2	2.2 ± 0.5	2.2 ± 0.7	3.0 ± 0.6	3.0 ± 0.8	2.2 ± 0.5	2.1 ± 0.5	2.9 ± 0.8	3.2 ± 0.9	2.1 ± 0.5	1.7 ± 0.8
PK ankle flexion angle (°)	86.1 ± 11.8	85.8 ± 12.4	87.7 ± 12.0	85.8 ± 17.5	85.4 ± 12.5	83.0 ± 12.9	89.1 ± 17.2	87.4 ± 19.1	84.1 ± 15.5	81.8 ± 12.5	92.5 ± 10.7	93.8 ± 9.5
PK ankle extensor moment (Nm·kg^{-1})	0.7 ± 0.4	0.8 ± 0.4	2.0 ± 0.6	2.1 ± 0.8	0.9 ± 0.6	0.8 ± 0.3	2.1 ± 0.7	2.0 ± 0.9	0.6 ± 0.4	0.6 ± 0.2	2.3 ± 0.7	2.5 ± 0.6

*AVE = average; PK = peak; vGRF = vertical ground reaction force; HGRF = horizontal ground reaction force; BM = body mass; D = dominant; ND = nondominant; LG = low group; MG = moderate group; HG = high group; WA = weight acceptance.

than FC. For PK knee extensor moment, there were no interactions, and there were no main effects for group or limb. However, there was a main effect for contact ($p < 0.001$), in which PEN were greater than FC.

For PK ankle flexion angle, there were no interactions or main effects. For PK ankle extensor moment, there were no interactions, and there were no main effects for group or limb. However, there was a main effect for contact ($p < 0.001$), in which FC were greater than PEN.

For 505_{mod} completion time, there was no interaction or main effects. Likewise, there was no interaction or main effects for both AVE HGRFR and PK HGRFR. For KAA, there was no interaction or main effect for group. However, there was a main effect for limb ($p = 0.048$), in which D were greater than ND. For KAM, there was no interaction or main effects (Table 5).

Discussion

The aim of this study was to investigate the effect of single-leg hop asymmetry on biomechanical characteristics during 180° CoD. To achieve this aim, the study had the following objectives: (a) investigate differences in braking strategy (PEN vs. FC) regarding the categorization of asymmetry during 180° CoD in team-sport players, (b) investigate differences in kinematics (lower-limb joint angles) and kinetics (GRFs and moments) between D and ND limbs during 180° CoD, and (c) explore kinematic and kinetic differences between PEN and FC of 180° CoD. Although previous studies have considered the influence of asymmetry on CoD speed (19,40,42), this is the first study to evaluate the interaction of PEN and FC on such factors. The results of this study indicate that the magnitude of asymmetry did affect the biomechanical characteristics of 180° CoD. These findings are in contrast with previous work (19,40,42), which found that asymmetry does not impact CoD speed. These results may be explained by the fact that subjects will adopt compensatory strategies during CoD tasks to successfully execute the movement.

The results revealed that for both 505_{mod} and 505, the PEN involved significantly greater PK vGRF, PK hip flexion angles, PK hip extensor moments, PK knee flexion angles, and PK knee extensor moments, but lower AVE vGRF, AVE horizontal GRF, and PK ankle extensor moments. For 505, the ND limb involved significantly greater PK vGRF, but the opposite was revealed for PK horizontal GRF. For 505_{mod}, the D limb involved significantly greater KAA. Finally, there was a significant interaction (group × limb) for PK HGRFR during 505. Therefore, it appears that asymmetry affects GRFs and KAAs during 180° CoD in team-sport players.

The results of this study indicate that significant differences existed between D and ND limbs for KAA during 505_{mod}, while significant differences existed for PK horizontal and vGRF during 505. This study is the first to examine the role of asymmetry on biomechanical characteristics during 180° CoD. The significant differences ($p = 0.048$) in KAAs between D and ND limbs may suggest that asymmetry may be a potential risk factor for injury during preplanned 180° pivoting (505_{mod}), regardless of magnitude. Previous research has shown KAA at FC to be significantly related ($r = 0.49$) to KAM during 180° pivoting. However, Jones et al. (34) examined KAA at IC, whereas this study evaluated KAA across the WA phase. The results of the current study contrast with preliminary work by Thomas et al. (55) who found KAAs to be greater ($p = 0.06$; $d = 0.63$) in the nonpreferred limb as compared with the preferred limb during 505_{mod}. However,

Table 2

Mean ± *SD* of force–time characteristics, joint angles, and moment characteristics between the weight acceptance phase of PEN and final contacts for the 505_{mod}.*

	LG				MG				HG			
	Penultimate contact		Final contact		Penultimate contact		Final contact		Penultimate contact		Final contact	
	D	ND	D	ND	D	ND	D	ND	D	ND	D	ND
Variable	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*
Force–time characteristics												
AVE vGRF (BM)	0.8 ± 0.2	0.8 ± 0.2	1.3 ± 0.2	1.3 ± 0.2	0.9 ± 0.3	0.8 ± 0.3	1.3 ± 0.2	1.3 ± 0.2	0.9 ± 0.2	0.9 ± 0.2	1.3 ± 0.1	1.3 ± 0.2
PK vGRF (BM)	2.3 ± 0.6	2.3 ± 0.6	1.8 ± 0.3	1.8 ± 0.3	2.5 ± 0.9	2.3 ± 0.7	1.9 ± 0.4	1.9 ± 0.4	2.2 ± 0.4	2.2 ± 0.5	1.8 ± 0.2	1.7 ± 0.3
AVE HGRF (BM)	0.5 ± 0.2	0.5 ± 0.1	1.0 ± 0.2	1.0 ± 0.2	0.5 ± 0.2	0.5 ± 0.2	0.9 ± 0.1	1.0 ± 0.1	0.6 ± 0.1	0.6 ± 0.1	1.0 ± 0.1	0.9 ± 0.2
PK HGRF (BM)	1.4 ± 0.4	1.5 ± 0.5	1.4 ± 0.3	1.4 ± 0.3	1.6 ± 0.7	1.5 ± 0.5	1.4 ± 0.3	1.5 ± 0.3	1.4 ± 0.4	1.5 ± 0.4	1.4 ± 0.1	1.3 ± 0.2
Joint kinematics and kinetics												
PK hip flexion angle (°)	89.9 ± 13.3	89.4 ± 14.1	61.2 ± 12.3	61.7 ± 10.5	88.8 ± 20.2	91.1 ± 16.5	60.4 ± 16.1	59.8 ± 13.7	86.4 ± 12.8	82.8 ± 8.9	58.6 ± 14.7	53.5 ± 13.6
PK hip extensor moment (Nm·kg^{-1})	2.6 ± 1.1	2.8 ± 1.0	2.5 ± 0.8	2.5 ± 0.8	2.7 ± 1.1	2.7 ± 1.0	2.2 ± 0.8	2.6 ± 0.8	2.4 ± 0.6	3.0 ± 1.2	2.3 ± 0.5	2.2 ± 0.7
PK knee flexion angle (°)	114.0 ± 13.9	112.5 ± 13.9	69.5 ± 7.9	68.0 ± 6.4	105.0 ± 21.3	109.8 ± 19.3	69.0 ± 6.4	66.9 ± 8.5	107.2 ± 11.9	105.5 ± 16.8	69.1 ± 9.6	66.0 ± 15.7
PK knee extensor moment (Nm·kg^{-1})	3.4 ± 1.1	3.4 ± 1.2	2.3 ± 0.4	2.3 ± 0.7	3.3 ± 1.1	3.1 ± 1.2	2.3 ± 0.7	2.3 ± 0.5	3.2 ± 0.6	3.2 ± 0.5	2.2 ± 0.5	1.7 ± 0.6
PK ankle flexion angle (°)	88.2 ± 10.9	87.3 ± 12.0	88.1 ± 12.4	85.9 ± 11.7	85.3 ± 11.6	85.4 ± 12.5	87.0 ± 18.2	86.8 ± 15.0	83.3 ± 12.0	84.8 ± 13.00	92.2 ± 9.9	92.0 ± 10.6
PK ankle extensor moment (Nm·kg^{-1})	0.7 ± 0.3	0.7 ± 0.4	2.0 ± 0.7	1.9 ± 0.7	0.9 ± 0.6	0.8 ± 0.4	1.9 ± 0.7	2.2 ± 0.8	0.6 ± 0.5	0.6 ± 0.4	2.2 ± 0.6	2.2 ± 0.5

*AVE = average; PK = peak; vGRF = vertical ground reaction force; HGRF = horizontal ground reaction force; BM = body mass; D = dominant; ND = nondominant; 505_{mod} = modified 505; LG = low group; MG = moderate group; HG = high group; WA = weight acceptance.

Thomas et al. (55) defined the preferred limb as the subjects would kick a ball, whereas this study defined the D limb from the furthest single-leg hop scores. Thus, this inconsistency may be because defining a "preferred" limb subjectively can negatively affect the interpretation of asymmetry (21). For example, players may perceive a limb to be "dominant" and may not truly be "dominant" based on the muscle strength quality or task being assessed. Furthermore, an abducted knee position may create a GRF acting laterally outside the knee, thus increasing the moment arm between the knee joint axis and vGRF vector, leading to greater KAMs (15,16).

The current study found that with both CoD tasks, significantly increased AVE VGRF during the FC as compared with the PEN were observed, substantiating previous research on 180° pivoting (25,32,35). By contrast, greater PK vGRFs were observed in the PEN as compared with the FC for 505_{mod}, in line with previous research (25,32). The current study found that increased AVE and PK HGRFs were observed in the FC compared with the PEN for both tasks. These findings are in line with previous work (32), who found greater AVE horizontal GRFs during the FC compared with the PEN in 180° pivoting. This braking strategy has also shown to significantly relate to greater knee extensor moments in the FC during 180° pivoting (25). Taken together, these findings may indicate that, during 180° CoD, more substantial braking takes place during the FC compared with the PEN, due to the need to reduce the body's momentum to zero before pivoting, and reaccelerating.

The joint angle data revealed that in both tasks, greater PK hip and knee flexion angles were observed during the PEN compared with FC. These results are consistent with previous research (32,54,55), who found PK hip and knee flexion angles to be significantly greater during the PEN compared with FC. These results are likely to be related to subjects adopting a certain braking strategy, regardless of whether trials were performed when turning off their D or ND limb. For example, it is likely athletes use greater hip and knee flexion during the PEN to facilitate longer braking force, thus impulse (change in momentum), resulting in a greater reduction in whole-body velocity (impulse = change in momentum). This helps provide an optimal body position at FC (lower center of mass) allowing the FC limb to be planted out in front of the body. Indeed, Sheppard and Young (50) indicated technique to be a deterministic factor for CoD; thus, the findings of the current investigation may indicate technique to be more influential for CoD speed than asymmetry. Furthermore, high levels of isokinetic eccentric extensor strength are shown to be influential in decelerating during the PEN from faster approach velocities during 180° turns (35). A note of caution is due here because the current investigation only examined 180° CoD; therefore, it is unknown whether this notion would hold true for CoD of different magnitudes (e.g., 45°, 90°, and 135°). Further research should be undertaken to investigate the influence of asymmetry on lower-limb joint kinematics and kinetics during CoD between 45 and 135°.

In this investigation, greater PK hip and knee flexor moments were observed during the PEN compared with FC across both CoD tasks. These results are in accord with recent studies (32,54,55), indicating PK hip and knee flexor moments to be significantly greater during the PEN compared with FC. Contradictory, both tasks revealed greater ankle dorsiflexor moments during FC compared with PEN. These findings are in agreement with those obtained by (32), who found greater ankle dorsiflexor moments during FC compared with PEN. These results may be explained by the fact that subjects initially made the FC with

Table 3

Mean ± *SD* of completion time, braking force ratio, and knee abduction angle and knee abduction moment for the 505.*

	LG		MG		HG	
	D	ND	D	ND	D	ND
Variable	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*
Completion time (s)	2.55 ± 0.22	2.53 ± 0.22	2.56 ± 0.18	2.52 ± 0.14	2.54 ± 0.06	2.53 ± 0.09
AVE HGRFR	1.96 ± 0.43	1.91 ± 0.34	1.91 ± 0.62	1.95 ± 0.52	2.31 ± 1.12	1.93 ± 0.61
PK HGRFR	0.97 ± 0.25	0.98 ± 0.26	0.85 ± 0.22	1.00 ± 0.28	1.22 ± 0.63	0.92 ± 0.32
KAA (°)	8.84 ± 6.71	9.49 ± 10.45	8.54 ± 5.92	8.50 ± 6.77	8.54 ± 4.33	6.29 ± 4.47
KAM (Nm·kg^{-1})	0.87 ± 0.39	0.87 ± 0.38	0.86 ± 0.40	1.00 ± 3.40	0.69 ± 0.22	0.59 ± 0.24

*AVE = average; PK = peak; HGRFR = horizontal ground reaction force ratio; KAA = knee abduction angle; KAM = knee abduction moment; D = dominant; ND = nondominant; LG = low group; MG = moderate group; HG = high group.

a forefoot plant, evoking an ankle dorsiflexor moment, whereas during PEN, an initial rearfoot plant may have led to greater plantar flexor moments. These factors may explain the lack of interaction or main effects for KAM, given previous research has shown rearfoot plants to produce greater KAM during 180° pivoting (13). Taken together, these findings indicate that the braking strategies for both tasks in the sagittal plane has greater emphasis on counteracting hip and knee flexor moments during the PEN, as compared with ankle dorsiflexor moments during the FC.

The current study found a significant interaction (group × limb) for PK HGRFR during 505. These findings suggest the magnitude of asymmetry and the turning limb (D or ND) influences HGRFR during the PEN relative to the FC. The PK HGRFR for the MG was greater for the ND limb compared with the D limb, but the opposite was revealed for the HG. Thus, the MG produced greater horizontal braking during the FC (relative to the PEN) on the ND limb compared with the D limb. Yet, for the HG, greater horizontal braking occurred during the FC on the D limb compared with the ND limb. This finding suggests that the MG group may have adopted a different braking strategy to distribute the PK HGRFs depending on whether turning off their D or ND limb. It may be possible that in the HG, when turning off their ND limb, subjects made better use of the PEN as compared with the MG. Recent work has shown faster CoD speed to exhibit lower HGRFRs as compared with slower CoD speed, while earlier studies found lower HGRFRs to associate with lower KAM in pivoting (34) and cutting (33). Another possible explanation for this is that when turning off the D limb, subjects in the HG may have approached the CoD faster, creating an increase in HGRF in the FC. As a result, the ND limb may have been less able to accept the forces in the PEN, and thus, less braking occurs during this contact resulting in greater PK HGRFRs favoring the FC. This finding suggests that CoD technique is not consistent between limbs and has important implications for training and monitoring and may present a potential problem in the future. For example, subjects may possibly adjust at the joint or segment level, which may present a potential problem in the long term. For example, if physical demand is not evenly evident across all joints and both limbs, this may create increased loads with respect to injury risk. This is an important issue for future research.

The current study found has demonstrated that asymmetry impacts the biomechanical characteristics of 180° CoD. These results are in contrast with data obtained in earlier studies, which showed that asymmetries did not negatively impact CoD speed (19,40). However, it should be noted that previous work has only evaluated CoD ability by measuring CoD speed only, whereas the current study assessed both the biomechanical characteristics and CoD speed of 2 180° CoD tasks. Statistically and practically, significant differences (p = 0.000; d = 2.35–5.08) existed in asymmetry ratios among groups, resulting in cutoff frequencies 3.18, 6.48, and 12.39% for the LG, MG, and HG, respectively. Thus, it can therefore be suggested that asymmetry ratios of ≥6.48% in single-leg hop scores impact the biomechanical characteristics of 180° CoD but do not influence CoD speed. However, these findings cannot be extrapolated to all measures of asymmetry and CoD, given their multifactorial nature. It is unknown whether these findings would remain if an alternative test was used to determine asymmetries (isokinetic dynamometry, for example). This is an important issue for future research.

A limitation of this study is that subjects were tested during the preseason period; therefore, findings may change during the in-season period due to competition and training. Second, being limited to 24 male and 28 female subjects, sport and positional comparisons were unable to be performed. Future research should further examine the influence of asymmetry on

Table 4

Mean ± *SD* of completion time, braking force ratio, and knee abduction angle and knee abduction moment for the 505_{mod}.*

	LG		MG		HG	
	D	ND	D	ND	D	ND
Variable	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*	Mean ± *SD*
Completion time (s)	2.79 ± 0.21	2.78 ± 0.20	2.80 ± 0.19	2.75 ± 0.18	2.79 ± 0.11	2.80 ± 0.08
AVE HGRFR	2.09 ± 0.69	1.99 ± 0.36	1.90 ± 0.49	2.01 ± 0.46	1.89 ± 0.40	1.71 ± 0.41
PK HGRFR	1.05 ± 0.33	1.01 ± 0.27	1.02 ± 0.34	1.07 ± 0.29	1.08 ± 0.29	0.93 ± 0.20
KAA (°)	9.28 ± 7.21	7.40 ± 5.46	9.87 ± 5.96	8.50 ± 5.32	7.98 ± 3.78	6.24 ± 4.82
KAM (Nm·kg^{-1})	0.84 ± 0.39	0.80 ± 0.30	0.81 ± 0.23	1.00 ± 0.44	0.61 ± 0.16	0.58 ± 0.22

*AVE = average; PK = peak; HGRFR = horizontal ground reaction force ratio; KAA = knee abduction angle; KAM = knee abduction moment; D = dominant; ND = nondominant; 505_{mod} = modified 505; LG = low group; MG = moderate group; HG = high group.

Table 5

Repeated-measures analysis of variance statistics for biomechanical and global measures of 505 and 505_{mod} change of direction.*

	505				505_{mod}		
	Main effects		Interaction		Main effects		Interaction
Variable	Group	Limb	Group × limb	Variable	Group	Limb	Group × limb
Completion time (s)	$F_{2,49} = 0.001$ $p = 0.999$ $\eta_p^2 = 0.000$	$F_{1,49} = 2.705$ $p = 0.106$ $\eta_p^2 = 0.052$	$F_{2,49} = 0.283$ $p = 0.755$ $\eta_p^2 = 0.011$	Completion time (s)	$F_{2,49} = 0.033$ $p = 0.967$ $\eta_p^2 = 0.001$	$F_{1,49} = 1.156$ $p = 0.287$ $\eta_p^2 = 0.023$	$F_{2,49} = 0.841$ $p = 0.437$ $\eta_p^2 = 0.033$
AVE HGRFR	$F_{2,49} = 0.538$ $p = 0.587$ $\eta_p^2 = 0.021$	$F_{1,49} = 3.483$ $p = 0.068$ $\eta_p^2 = 0.066$	$F_{2,49} = 2.740$ $p = 0.074$ $\eta_p^2 = 0.101$	AVE HGRFR	$F_{2,49} = 1.095$ $p = 0.343$ $\eta_p^2 = 0.043$	$F_{1,49} = 0.423$ $p = 0.519$ $\eta_p^2 = 0.009$	$F_{2,49} = 0.744$ $p = 0.480$ $\eta_p^2 = 0.029$
PK HGRFR	$F_{2,49} = 0.695$ $p = 0.504$ $\eta_p^2 = 0.028$	$F_{1,49} = 1.21$ $p = 0.277$ $\eta_p^2 = 0.024$	$F_{2,49} = 6.21$ $p = 0.004$ $\eta_p^2 = 0.202$	PK HGRFR	$F_{2,49} = 0.064$ $p = 0.938$ $\eta_p^2 = 0.003$	$F_{1,49} = 0.686$ $p = 0.411$ $\eta_p^2 = 0.014$	$F_{2,49} = 0.738$ $p = 0.483$ $\eta_p^2 = 0.029$
KAA (°)	$F_{2,49} = 0.252$ $p = 0.778$ $\eta_p^2 = 0.010$	$F_{1,49} = 0.114$ $p = 0.737$ $\eta_p^2 = 0.002$	$F_{2,49} = 0.424$ $p = 0.657$ $\eta_p^2 = 0.017$	KAA (°)	$F_{2,49} = 0.351$ $p = 0.706$ $\eta_p^2 = 0.014$	$F_{1,49} = 4.098$ $p = 0.048$ $\eta_p^2 = 0.077$	$F_{2,49} = 0.042$ $p = 0.959$ $\eta_p^2 = 0.002$
KAM (Nm·kg^{-1})	$F_{2,49} = 2.53$ $p = 0.090$ $\eta_p^2 = 0.094$	$F_{1,49} = 1.87$ $p = 0.178$ $\eta_p^2 = 0.037$	$F_{2,49} = 2.31$ $p = 0.110$ $\eta_p^2 = 0.086$	KAM (Nm·kg^{-1})	$F_{2,49} = 2.909$ $p = 0.064$ $\eta_p^2 = 0.106$	$F_{1,49} = 0.936$ $p = 0.338$ $\eta_p^2 = 0.019$	$F_{2,49} = 2.750$ $p = 0.074$ $\eta_p^2 = 0.101$

*AVE = average; PK = peak; HGRFR = horizontal ground reaction force ratio; KAA = knee abduction angle; KAM = knee abduction moment; 505_{mod} = modified 505.

CoD biomechanics between sport and positions within sports. Since the study was limited to 180° CoD, it is not possible to generalize these findings to CoD tasks (45°, 90°, 135°). Apart from KAA and KAM, this study only featured lower-limb joint angles and moments in the sagittal plane. Despite hip abduction and rotation angles, such as the motion on the frontal and transversal planes, are commonly investigated in cutting studies, whole-body deceleration takes place in the sagittal plane during 180° COD. Therefore, only sagittal plane joint angles and moments were considered here. An issue that was not addressed in this study was whether movement variability between trials (on the same limb) influenced the findings. Although we do acknowledge single-leg hop asymmetry was based on average profiles, it is likely there will be some form of movement variability between trials (on the same limb). Despite this limitation, the study certainly adds to our understanding of the effect of single-leg hop asymmetry on CoD biomechanics. Further research could also be conducted to determine the role of movement variability on such measures.

In summary, this study has shown that asymmetry influences lower-limb kinematics and kinetics during 180° CoD but does not affect CoD speed. This research has also shown that differences in lower-limb kinematics and kinetics were observed between PEN and FC during 180° CoD. The current data highlight the importance of technique and asymmetries during CoD speed and may suggest that asymmetry ratios of ≤6.48% in single-leg hop scores within team-sport players influence lower-limb biomechanical characteristics, specific to 180° CoD. Because this investigation was limited to 180° CoD tasks, it is not possible to extrapolate these findings to other CoD tasks (45°, 90°, and 135°). Future research could usefully explore alternative assessments (countermovement jump, isometric midthigh pull, and isokinetic dynamometry) to assess asymmetries and its impact on both categorization of asymmetries and lower-limb kinematics and kinetics during CoD speed. It would be interesting to assess the effects of sport on the interaction between asymmetries and braking strategy during CoD speed during either pivoting (135°, 180°) or cutting (45°, 90°) maneuvers. A natural progression of this investigation is to perform 180° CoD in unanticipated conditions to increase ecological validity and the application to a real-world scenario due to increased task complexity. This would be a fruitful area for further work.

Practical Applications

The findings from this study show the level of asymmetry influences the interaction of horizontal GRF between PEN and FC; thus, subjects will adopt an alternative braking strategy to distribute GRF dependent on turn limb to achieve a given performance. As such, coaches and practitioners should consider developing their athlete's ability to utilize the PEN or enhance physical capacities (neuromuscular control and muscular strength) to withstand the increased loading in the FC. In addition, turning off the D limb showed increased KAA; thus, coaches and practitioners are encouraged to coach a 180° CoD strategy, which emphasizes loading in the sagittal plane (hip, knee, and ankle alignment) and limits a "knee valgus" position due to its link with KAM and increased ACL strain. Finally, differences in braking strategy (PEN vs. FC) are evident, and as such, coaches and practitioners are recommended to coach a 180° CoD strategy, which emphasizes triple flexion of the hip, knee, and ankle in the PEN to lower the COM, facilitate an effective braking position, and effectively align the body toward the intended direction of travel. To create appropriate training programs to enhance performance while reducing the potential for risk of injury, an understanding of the mechanics necessary for successful CoD and their relationship with lower-limb joint angles, GRFs, and moments is needed. These findings demonstrate the significance of assessing both limbs during strength and testing, and both foot contacts and directions when assessing biomechanical characteristics of CoD.

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