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Article *in* Strength and conditioning journal · May 2018

DOI: 10.1519/SSC.0000000000000395

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Strength and Conditioning Journal Publish Ahead of Print
DOI: 10.1519/SSC.0000000000000395

The Role of the Penultimate Foot Contact During Change of Direction: Implications on Performance and Risk of Injury

Review article

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Abstract word count: 100 words

Manuscript word count: 4463 words

Number of tables and figures: 3 Tables, 5 Figures

Abstract

Most change of direction biomechanical investigations and current technique guidelines focus on the role of the final foot contact (plant foot contact). However, it is evident that the braking characteristics during the penultimate foot contact play an integral role in deceleration prior to directional changes ≥ 60˚; and can therefore, be described as a "preparatory step". In this review, we examine the role of the penultimate foot contact on change of direction performance and associated biomechanical injury risk factors, and provide technical guidelines for coaching the "preparatory step" during change of direction, to enhance performance and reduce risk of injury. A VIDEO ABSTRACT DESCRIBING THIS ARTICLE CAN BE FOUND IN SUPPLEMENTAL DIGITAL CONTENT 1 (SEE VIDEO, HTTP://

LINKS.LWW.COM/SCJ/A240)

Key words: cutting; turning; deceleration; braking; anterior-cruciate ligament; knee abduction moments

INTRODUCTION

The ability to change direction is an integral component of multidirectional sport, such as evading an opponent or reacting to a ball (5, 70, 72, 85, 86, 92). However, directional changes are also a key action associated with non-contact anterior cruciate ligament (ACL) injuries (6, 7, 10, 18, 46, 59, 64, 91), which have devastating health (27, 52), psychological (27, 49) and economic (12, 27) implications for athletes. Therefore, understanding the biomechanical risk factors and mechanical determinants of faster change of direction (COD) performance are of great interest to practitioners.

Most COD biomechanical investigations have generally explored the kinetic, kinematic and technical determinants of the plant limb (final foot contact or push-off limb phase) from both performance and risk of injury perspectives (14, 15, 34, 47, 56, 58, 77-79, 81, 82). Additionally, COD guidelines also predominantly emphasize and provide technical and coaching guidelines for the plant phase (final foot contact) of directional changes (24, 33, 35, 63, 96). However, changing direction can be described as a multi-step action, whereby preliminary deceleration occurs over several steps, to reduce momentum, especially when running at high speeds and executing extreme angled directional changes (1). Patla et al. (67,

68) states that directional changes must be planned and initiated in the step before the turn to facilitate effective COD performance. This is substantiated by previous studies that have reported athletes make anticipatory postural adjustments (APA) in the step prior to (penultimate foot contact (PFC)) the COD (final foot contact (FFC)), demonstrating kinematic changes in foot placement, trunk lean and rotation, and head rotation (37, 51, 60, 69, 93, 95). Furthermore, braking characteristics such as greater braking forces and external knee flexor moments (KFM) have been reported in the step prior (PFC) to CODs ≥ 60˚ (20, 25, 42-45), highlighting the importance of the PFC during extreme directional changes.

The findings of previous research have shown soccer players perform ~100 CODs of 90-180˚ during a soccer match (5), while Robinson et al. (70) reported ~80 CODs of 45-135˚ and ~20 turns ≥ 135˚ in soccer matches from a minimum approach velocity of 4 $m.s^{-1}$. Furthermore, Sweeting et al. (85) recently reported that 90˚ and 180˚ turns are frequently performed movements in netball, and the 180° turn is a fundamental movement for cricket batsmen whereby approximately 40 turns will be performed when scoring 100 runs during a match (17). As such, the aforementioned studies highlight the importance of extreme CODs in sport. For cuts and turns ≥ 60˚ there would be a requirement to reduce the velocity into the COD, thus momentum (22, 23, 25, 40), and as such, the preceding footfalls would be effective for deceleration prior to changing direction (1, 16, 20, 25, 40, 42-45, 62, 71). To execute extreme CODs changes efficiently, a multi-step strategy will undoubtedly be adopted by athletes (1, 16, 20, 25, 40, 42-45, 62, 71). Surprisingly, a limited number of investigations have inspected the PFC when examining COD biomechanics from both performance (16, 20, 40) and risk of injury perspectives (21, 42-45), and to our knowledge, no clear coaching and technical guidelines for the PFC when changing direction exist. Analysis into the braking characteristics can provide greater understanding into the optimal braking strategies which could mitigate risk of knee injury during the FFC, where ACL injuries occur (6, 7, 10, 18, 46, 59, 64, 91), but also provide insight into deceleration strategies effective for COD performance (16, 20, 40).

The aim of this review is to examine the role of the PFC when changing direction, outlining the critical characteristics associated with the deceleration phase, while considering the implications on performance and risk of injury. In addition, to assist strength and conditioning coaches in their understanding of how to coach and condition their athletes for better COD ability, technical and coaching guidelines for preliminary deceleration during the PFC are also provided, with recommendations of how to integrate braking strategy training into a holistic training program.

For the purpose of this review the PFC is defined as “the 2nd last foot contact with the ground prior to moving into a new intended direction” (16, 42-44) and is synonymous with studies which have described the PFC as the “support foot” (51), “pre COD phase” (93), “approach step” (25), “pre turn step” (62), “one step before” (60) and “before step” (45). Furthermore, FFC is defined as “the phase during a cut or pivot when an individual makes contact with the ground and initiates movement into a different direction” (16, 42-44) and is synonymous with studies which have described the FFC as the “push-off foot” (51), “COD phase” (93), “execution step” (25), “pivot step” (62) “cutting step” (45) and plant foot/phase (81, 82). Additionally, CODs between angles 0-45˚, 45-90˚ and >90˚ are referred to as acute, moderate and extreme.

Role of preliminary deceleration for COD: kinetic and kinematic differences between the PFC and FFC

A summary of research that has compared PFC and FFC biomechanics during COD is presented in Table 1. Nedergaard et al. (62) used accelerometers and three-dimensional (3D) motion analysis to compare the mechanics during the FFC with those during the preceding footfalls (PFC and ipsilateral). The authors observed greater trunk decelerations and peak joint flexion velocities in the preceding two footfalls compared to the FFC during a 135° ‘v’ cut, highlighting the importance of preliminary deceleration prior to the COD. This finding substantiates Andrews et al. (1) qualitative assessment of cutting stating preliminary deceleration of several steps is key prior to executing a COD. Additionally, Rovan et al. (71) also highlighted the importance of the two steps prior to the FFC during a range of angled directional changes (30°, 60°, 90°, 120°, 150° and 180˚). Based on GPS and high-speed video analysis data the authors reported soccer players start changing direction prior to the FFC, particularly during the PFC, to facilitate the COD. Furthermore, Hader et al. (22, 23) recently showed that reductions in velocity are present, particularly when performing grater angled CODs reporting deceleration distances of 4.3 ± 1.9 and 7.1 ± 1.2 m prior to executing 45° and 90° cuts, from a 10 m approach, respectively. Collectively, these results indicate the preceding footfalls are undoubtedly required for effective deceleration prior to the COD.

However, a limitation of the abovementioned studies is only the kinematics of the preceding footfalls were established with no kinetic information regarding the joint moments or braking forces.

Havens and Sigward (25) investigated the PFC and FFC ground reaction force (GRF) properties and ground contact times (GCT) during a 45° and 90° cut, reporting significantly greater ($p<0.001$) posterior braking force and posterior ground reaction impulse (GRI) in the PFC compared to the FFC for the 90° cut only. No differences in GRI in both contacts during the 45° cut were reported (25), suggesting the braking demands were evenly spread across both footfalls. Conversely, a disproportionately greater braking force and impulse was required in the PFC compared to the FFC for the 90° cut, emphasizing the importance of the posterior braking force and impulse in the PFC for extreme cuts (29). These findings are supported by recent studies that have also reported significantly greater PFC braking forces during 60˚ cuts (45), 90° cuts (42, 43) and 180˚ turns (20, 42, 44) compared to FFC. This could be attributed to CODs >45˚ requiring greater reductions in velocity and momentum (22, 23, 25), thus earlier braking is required to allow effective redirected propulsion force and impulse during the FFC into the new intended direction. Furthermore, higher approach velocities into CODs are also a critical factor influencing the braking characteristics associated during the PFC, as greater posterior impulse and peak external KFMs have been reported during fast 60° cuts (5.51 ± 0.32 vs 4.53 ± 0.33 $m.s^{-1}$) compared to slower cuts, respectively. Conversely, the requirements for preliminary deceleration and reductions in velocity prior to the COD for acute CODs (23, 25) may be minimal, and as such, maintaining velocity may be of greater importance during these tasks.

Recently, Jones et al. (42) conducted the most comprehensive biomechanical comparison between the braking characteristics of the PFC and FFC during 90˚ cuts and 180˚ turns. Interestingly, significantly greater horizontal braking force (HBF), horizontal braking impulse (HBI), peak hip and knee flexion angles, and peak ankle plantar flexor moments were observed in the PFC compared to FFC during 90˚ cuts. Conversely, for 180˚ turns, significantly greater normalised vertical braking force (VBF), HBF, peak knee flexion angles and ankle dorsi flexion angles, peak and average KFMs, and peak ankle plantar flexor moments in the PFC were demonstrated compared to the FFC. These results support Graham-Smith et al. (20) who also documented greater peak HBF, peak VBF and peak KFMs in the

PFC during 180˚ turns, and support the findings of previous research that reported greater knee flexion angles and range of motion in the PFC compared to FFC (21).

Notably, Jones et al. (42) described the role of the PFC as a "preparatory step" observing knee and hip flexion throughout the stance phase which is maintained from transition of PFC to FFC. This facilitates GRF absorption through a greater range of motion, most likely in the sagittal plane (depending on COD angle) and provides an optimal body position at FFC (i.e., lower center of mass and allows the FFC leg to be planted out in front of the body). This supports Andrews et al. (1) early concept of the PFC serving as a key step in the facilitation of directional changes.

Role of PFC braking characteristics on associative knee injury risk factors during COD

Although previous studies have shown promising results regarding the role of the PFC for deceleration (21, 25, 45, 62), a shortfall of these studies are they have failed to inspect the relationships between PFC kinetic and kinematic variables with associated knee injury risk factors, such as knee abduction moments (KAM) and internal rotation moments. These aforementioned moments can increase ACL strain (53-55, 75, 76, 94) and importantly, greater KAMs has been shown to be a predictor of non-contact ACL injury in adolescent female athletes (29). Jones et al. reported greater peak HBF in the PFC compared to the FFC during cutting (43) and pivoting (44) in female soccer players. However, no significant relationships were observed between the magnitude of peak HBF and KAMs, and no significant relationships between HBF ratio (defined as FFC braking force / PFC braking force) and KAMs for both 90° cut and 180° pivot performance, respectively. The authors attributed the lack of relationships to the low sample sizes of 26 and 27, respectively. Interestingly, players with greater KAMS in both studies (Table 1) had a higher HBF ratios compared to players displaying lower KAMs, highlighting the importance of producing greater magnitudes of HBF in the PFC, relative to the FFC.

Jones et al. (43, 44) considered only peak braking force-time variables which is only representative of one instance of the force-time data. Inspecting this variable only, does not provide further insight into the "braking effect" and considering variables such as average HBF and impulse could provide greater insight into braking characteristics during the weight acceptance phase of the PFC (i.e., impulse (force × time) = change in momentum- greater average forces over weight acceptance would facilitate effective braking). Recently, Jones et al. (42) considered the aforementioned variables demonstrating lower KAMs during pivoting were associated with a lower average HBF ratio (Table 1), therefore, indicating a greater proportion of braking in the PFC, relative to the FFC, may reduce knee joint loading. Furthermore, PFC average HBF was inversely associated with 90° cut KAMs (Table 1).

Collectively, these findings although preliminary, could have large practical applications regarding ACL injury reduction programmes, whereby a COD technique which emphasizes greater braking (magnitudes of HBF) during the PFC, where the knee goes through a greater range of knee flexion (21, 42) and generally performed in the sagittal plane, may alleviate KAMs in the FFC (turning or cutting limb) (42-44); which is the limb that gets injured during CODs (6, 7, 10, 18, 46, 59, 64, 91). If the braking strategy is emphasized toward the final step this will increase the resultant GRF, which could increase peak knee abduction moments (42), thus risk of injury (29). Dempsey et al. (14) has documented a 36% reduction in peak KAMs (knee valgus moments) as a result of six weeks sidestep technique modification which focused on altering foot plant distance (closer to midline) and trunk control (upright trunk), while Jones et al. (41) has also demonstrated a reduction on KAMs following a six-week technique modification intervention. Therefore, practitioners should consider integrating braking strategy technique modification training into their injury reduction programs.

Role of PFC braking characteristics on COD performance

From a performance perspective, promising results have been demonstrated regarding the braking characteristics of the PFC (16, 20, 40) (Table 1); however, to our knowledge only three studies have conducted such analysis. Graham-Smith et al. (20) reported faster 180˚ turning performance was associated with greater PFC and FCC peak HBFs, and greater peak HBFs were significantly related to greater external KFMs in the PFC and FFC (Table 1). Though, it is worth noting that greater peak HBFs, and peak KFMs were demonstrated in the PFC (Table 1), therefore, highlighting the importance of braking in the PFC. However, these results were only published in a low sample size (n=12).

In a larger sample (n=40), Dos'Santos et al. (16) reported significant relationships between PFC peak HBF and peak HBF ratio with modified 505 left performance (Table 1). Furthermore, faster athletes demonstrated greater PFC HBFs and lower HBF ratios compared to slower athletes (Table 1). Recently, Jones et al. (40) reported stronger female soccer players (eccentric knee extensor peak torque) demonstrated faster 505 performance, greater approach velocities and greater reductions in velocity during the PFC in comparison to weaker subjects (Table 1). Notably, the stronger athletes produced greater PFC peak and average horizontal GRFs, and greater PFC external hip flexor moments (HFM) compared to weaker subjects (Table 1). Therefore, these results indicate that eccentrically stronger athletes possessed a greater capacity to tolerate the higher approach velocities during the COD (82). Moreover, their ability to produce greater horizontal braking forces and HFMs over the PFC, enabled greater reductions in velocity, which subsequently facilitated faster COD performance.

Collectively, the results of the abovementioned research suggest that greater magnitudes of HBF (peak and average) during the PFC, relative to the FFC, is advantageous for 180° COD performance; highlighting the PFC and steps prior to directional changes are important in the interaction between strength, speed and COD technique. Furthermore, from a performance perspective, braking earlier should reduce the horizontal momentum of the centre of mass (COM) to allow more effective weight acceptance and preparation for the drive-off phase of directional changes (16, 36, 40, 43). However, the abovementioned studies are only representative of 180° tasks and as the biomechanical demands are angle dependent (3, 11, 22, 23, 25, 26, 73, 74, 77), evaluations of the PFC braking characteristics of different angled cuts and turns from a performance perspective warrant further investigation.

Insert Table 1 about here

Effect of anticipation on PFC COD biomechanics

There is a paucity of research which has inspected the PFC during unplanned CODs, and these studies are mostly limited to sidesteps ≤ 45° (51, 60, 93), with only one study investigating extreme CODs (90° and 180°) (39). Mornieux et al. (60) examined the PFC during a pre-planned and unplanned 45° sidestep (light signal produced 850, 600 and 500 ms prior to COD) observing significantly less head rotation towards the direction of travel and greater rotation of the trunk to the opposite direction, in comparison to pre-planned and 850 ms unanticipated conditions. Moreover, a trend in less medial placement of the PFC was also documented during the unplanned conditions (600 and 500 ms). Similarly, Lee et al. (51) and

Wheeler et al. (93) reported a medial placement of the PFC (across pelvic midline) resembling a cross over cut (XOC) (Figure 1) during pre-planned sidesteps, which helps facilitate the directional change due to effective alignment into the intended direction of travel. This contrasts to the different lateral foot placement position (laterally from pelvic midline – not resembling XOC) during unplanned sidesteps with increased temporal constraints (Figure 1). Consequently, practitioners and coaches should acknowledge these technical differences (i.e. head and trunk rotation, and PFC foot placement) when coaching and screening pre-planned and unplanned sidesteps (Figure 1).

Insert Figure 1 about here

It is worth noting, that the abovementioned studies have not considered the braking characteristics (GRF and joint moments) of the PFC during a 45° sidestep. However, as Havens and Sigward (25) reported minimal differences in braking forces between straight run and 45° cuts (25), and the finding that minimum speed during a 45° COD is a determinant of faster performance (23); there may be a limited role for braking during PFC and preliminary deceleration for 45° cuts, compared to extreme CODs. Interestingly, Jones et al. (39) is the only study to our knowledge comparing braking characteristics between pre-planned and unplanned (light stimulus) COD tasks, reporting less braking takes place during the PFC of unplanned 90° cuts and 180° turns, compared to pre-planned. This opens a potential avenue for future research regarding improving the ability to anticipate and thus, make better postural adjustments prior to FFC to lower hazardous loading patterns during the FFC. Further research is necessary to investigate the role of the PFC during unplanned conditions; specifically, utilizing a sports-specific stimulus, as the type of stimuli can also influence COD biomechanics (50).

PRACTICAL APPLICATIONS: PENULTIMATE FOOT CONTACT COACHING AND TECHNICAL GUIDELINES

Athletes should make whole-body postural adjustments in order to execute moderate and extreme directional changes safely and efficiently (1, 37, 42, 50, 51, 60, 67-69, 93, 95). Technical factors such as foot placement, adjustment of steps, and body lean and posture have been identified as determinants of COD ability (96-98). Thus, it is imperative that athletes adopt technically efficient whole-body postures over the PFC (preparatory step) and potentially the steps before the PFC to facilitate effective COD (subject to angle and entry velocity). However, in order to execute efficient braking strategies, athletes should possess high levels of eccentric strength to tolerate the forces associated during the braking phase (13, 38, 40, 83, 88). Technical and coaching guidelines are presented in Table 2 for the PFC during extreme cuts and turns based on the findings and suggestions of previous research, and biomechanical principles (31, 32, 37, 40, 42-44, 60, 67, 87).

Insert Table 2 about here

Preparatory step guidelines for sharp angled cuts

Briefly, technical characteristics for braking during PFC (Table 2) involve creating a large COM to center of pressure (COP) distance, via anterior placement of the PFC in front of the body, and a backward lean of the trunk to shift the COM posteriorly. This emphasizes a posteriorly directed force vector, and maximises HBF to reduce momentum (impulse = change in momentum) prior to the push-off phase (32, 40, 42-44). Simultaneous, hip, knee (up to ~100˚) and ankle dorsi-flexion occurs, in order to absorb the loading in the sagittal plane (facilitates longer braking force application, thus impulse), and lower the COM for better stability (32, 42, 87). This occurs over a GCT of 0.15-0.40 s (influenced by entry velocity and angle of COD) (16, 25, 45, 62). Practitioners should be aware of knee alignment during the PFC when screening and coaching COD technique (Figure 2). The head and trunk should be directed forward, or some athletes may choose to rotate slightly towards the intended direction of travel (37, 60, 67) for effective realignment into the new intended direction, and earlier visual scanning of the situation (31).

Preparatory step guidelines for pivots

To minimise injury risk whole body deceleration should be performed in the sagittal plane (44, 57); however, for directional changes to be performed as fast as possible, athletes may decide to pre-rotate (their whole body) in the transverse plane during the PFC. If this is performed, then the coaching principles outlined for cutting should be predominantly followed (Table 2), such as the emphasis on backward trunk lean, a large COM to COP distances to encourage a posteriorly directed force vector for braking and reducing the velocity of COM, and exhibition of ankle (dorsi), knee and hip flexion. However, for 180° turns, athletes may perform the preparatory step in an externally rotated (transverse) position;

though, still emphasizing a posteriorly directed force vector due to foot placement in front of the COM and backwards trunk lean (Figure 3a). If this strategy is adopted, it is imperative not to evoke knee valgus. By performing this movement in a rotated position, this may facilitate faster performance due to effective realignment into the new intended direction (26, 77).

Braking strategy variance

Practitioners should acknowledge the variance in braking strategies adopted by athletes. For example, Figure 5A illustrates an athlete demonstrating a bilateral braking strategy during a 180° turn, whereby the foot involved with PFC remains in contact with the ground during the braking phase of the FFC. This technique facilitates and distributes the loading across two-foot contacts, thus maximising braking impulse over the PFC due to the longer GCT, and potentially lowering forces during the FFC. Conversely, illustrated in Figure 5B, athletes may adopt a clear flight phase between the PFC and FFC during a 180° turn, whereby the athlete will rotate their whole body during this flight phase in order to align themselves into the intended direction.

Insert Figure 3 about here

Different cutting strategies have been previously reported (knee, hip or ankle dominant) in male athletes (19), while females high school athletes are found to display different biomechanical deficits (quadricep, ligament, trunk and leg dominance) (66). In this review we have qualitatively identified two different 180° turning strategies (Figure 3); turning strategy A may be safer from an injury reduction perspective due to the capacity to distribute loading across two-foot contacts. From a performance perspective both techniques may be equally effective; however, further research is required quantitatively comparing the aforementioned turning strategies. Although, it should be noted that certain whole-body postures may induce greater 'injury risk', but may be optimal for performance, thus practitioners should acknowledge the 'performance-injury' conflict when coaching and screening COD. Additionally, it should be noted that the deceleration requirements will be dictated by the angle and entry velocity into the COD, thus, deceleration maybe accomplished over several steps, so the steps prior to the PFC will also be important (22, 23, 62). Therefore, the coaching guidelines presented in Table 2 for the PFC should also be applied when coaching deceleration during several steps.

Preparatory step for angled runs and lateral shuffle

The technical guidelines for the preparatory step are based on CODs from a straight approach (Table 2); however, athletes perform directional changes from angled and oblique runs (92), while lateral shuffles are also common actions in sports such as basketball and soccer (5, 86). We hypothesize the PFC plays an important role, serving as a "preparatory step" with slight differences in foot placement during such conditions. For example, performing a cut from an angled or oblique run the PFC may cross anteriorly and medially across the midline of the pelvis with the trunk positioned in the intended direction of travel (Figure 4). This aids deceleration by creating a posteriorly and medially directed GRF vector to reduce the momentum into the direction change. Subsequently, this will facilitate an optimal position for weight acceptance and push-off during the FFC. Similarly, when changing direction from a lateral shuffle, the PFC should be placed medially across the pelvic midline with trunk lean into the intended direction of travel to create a force vector in the frontal plane (Figure 4). This will help reduce the velocity of athlete via an appropriately directed braking force and suitable position for FFC.

Insert Figure 4 about here

Insert Figure 5 about here

PRACTICAL APPLICATIONS: TRAINING STRATEGY IMPLEMENTATION INTO THE WIDER TRAINING PROGRAM

In order to modify COD braking strategies of athletes, practitioners are recommended to perform two 15-30-minute COD technique sessions a week, with minimum 48 hours rest between sessions (following the abovementioned technical guidelines – coaching and teaching athletes to emphasize greater braking in the PFC relative to FFC, correct lower limb alignment, whole-body posture). Dempsey et al. (14) showed a 36% reduction in KAMs as a result of six weeks sidestep technique modification. Jones et al. (41) also noted a reduction in KAMs and improvements in 180˚ COD performance in female netballers due to a six-week technique COD modification intervention. Consequently, an example six-week braking strategy modification intervention is presented in Table 3, beginning with pre-planned low intensity decelerations and turns (weeks 1-2), before progressing intensity via velocity (45, 90) and angle (weeks 3-4), and introducing a stimulus with increased intensity (weeks 3-6). The example program is in accordance with NSCA COD recommendations (24), previous COD speed (8, 9) and COD technique interventions (14, 41). Although, it is worth noting that for training interventions to be a success, it is integral there is “buy in” from the coach and athletes (89), and high compliance (2, 27, 61, 65). Furthermore, appropriate feedback (biomechanical or video feedback to the athlete) between reps is also central to the success of training intervention (2, 27, 61, 65), with an external focus of attention recommended for improved retention (2).

Insert Table 3 about here

If practitioners and athletes have time constraints and cannot perform COD sessions, an alternative approach is to integrate braking strategy technique drills into the warm ups (neuromuscular training) of field and court based tactical/technical sessions to reduce biomechanical risk factors associated with injury (4, 48, 61, 80). Although, it should be noted, that a comprehensive training program which includes strength, plyometric (jump landing), speed, core and balance training, in addition to COD technique training may improve athletic performance and reduce risk of non-contact ACL injuries to a greater extent, than solely performing one training modality (4, 27, 28, 30, 65, 84). Therefore, practitioners are recommended to integrate the aforementioned training modalities into a holistic training program to optimally prepare, and enhance multidirectional athletes’ COD performance and reduce risk of injury.

CONCLUSIONS

It is evident that the PFC plays an important role in deceleration when changing direction, and can therefore, be considered as a “preparatory step”. Braking strategies which emphasize greater magnitudes of HBFs in the PFC, relative to the FFC, could reduce knee joint loading in the FFC, and facilitate faster performance (16, 40, 42-44). Thus, the role of the PFC should not be underestimated and overlooked when coaching and screening COD technique. Consequently, practitioners are encouraged to consider the role of the PFC during directional changes, and coach the "preparatory step" using the suggested technical guidelines outlined in this article when coaching COD technique.

Conflicts of Interest and Source of Funding: The authors report no conflicts of interest and no source of funding.

Figure 1. Differences in PFC placement relative to pelvic midline during unplanned and pre-planned 45˚ sidesteps. (Unplanned left image; pre-planned right image)

Figure 2. Athlete on the left demonstrating no knee valgus during PFC performed in the sagittal plane. Athlete on the right demonstrating knee valgus during PFC.

Figure 3. Illustration of braking strategy variance during 180˚ turns. Image A illustrates a bilateral braking strategy. Image B illustrates a clear flight phase and whole-body rotation between PFC and FFC (blue line represents force vector).

Figure 4. Role of the PFC during a cut from an angled approach sprint.

Figure 5. Role of the PFC during a lateral shuffle.

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Table 1. Summary of research that has examined the role of the PFC on injury risk factors, performance and comparisons to FFC

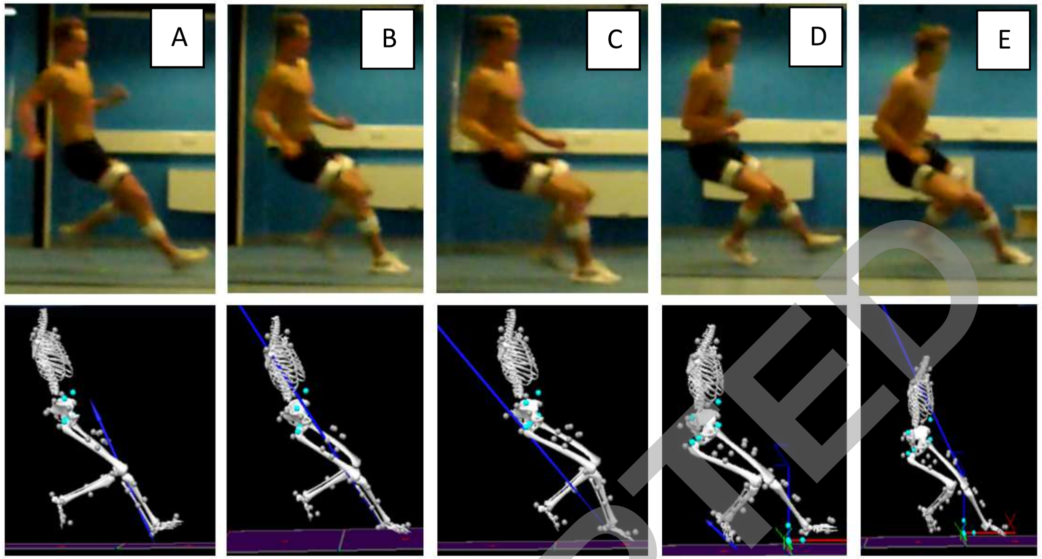
Study	Subjects (mean ± SD; age, height and mass)	COD task (Angle, velocity and pre-planned/ unplanned)	Kinetic and kinematic comparison between PFC and FFC	Role of PFC on KAMs	Role of PFC on COD performance (Association with completion time)
Jones et al. (43)	26 female soccer (21 ± 3.2 years, 1.68 ± 0.07 m, 59.1 ± 6.8 kg)	PP 5 x 3 m 90˚ cut (right foot plant) 4.42 ± 0.23 m.s^{-1}	PFC vs FFC: ↑ peak HBF	Subjects (n=7) with greater pKAMs (+0.5 SD above the mean) vs lower (n=8) (−0.5 SD below the mean) • ↑ peak HBF ratio (0.87 ± 0.04 vs 0.82 ± 0.04, ES = 1.25)	
Jones et al. (44)	27 female soccer (21 ± 3.8 years, 1.67 ± 0.07 m, 60.0 ± 7.2 kg)	PP 5 x 5m 180 pivot to the left (right foot plant) 4.02 ± 0.2 m.s^{-1}	PFC vs FFC: ↑ peak HBF	Subjects (n=9) with greater pKAMs (+0.5 SD above the mean) vs lower (n=9) (−0.5 SD below the mean) • ↑ peak HBF ratio (0.99 ± 0.24 vs 0.92 ± 0.18, ES = 0.33)	
Jones et al. (42)	Twenty-two female soccer players (21 ± 3.1 years, 1.68 ± 0.07 m, 58.9 ± 7.3 kg)	PP 5 x 3 m 90˚ cut 4.40 ± 0.22 m.s^{-1} PP 5 x 5m 180 pivot to the left (right foot plant) 4.03 ± 0.20 m.s^{-1}	• 90˚ CUT: PFC vs FFC: ↓ GCT, ↑ peak HBF, HBI, peak hip and knee flexion angles, peak ankle-plantar flexor moments • FFC vs PFC: ↑ average VBF, average HBF and greater average hip joint moment • 180˚: PFC vs FFC: ↓ GCT, ↑ peak VBF, peak HBF, ankle dorsi flexion angles, peak and average knee flexor moments and peak ankle plantar flexor moments • FFC vs PFC: ↑ average VBF, HBF, HBI and average hip joint moments during WA	180˚: Average HBF ratio (r = 0.466, r^2 = 22%, p = 0.029). 90˚ CUT: Average PFC HBF (r = -0.569, r^2 = 32%, p = 0.006).	
Havens & Sigward (25)	Twenty-five healthy soccer players (12 females) (22.4 ± 3.9 years; 1.74 ± 0.1 m; 70.9 ± 9.3 kg)	PP 15m Trials- 45° cut after 7.5m 5.83 ± 0.45 m.s^{-1} 90° cut after 7.5m 4.72 ± 0.35 m.s^{-1}	• 90˚ CUT: PFC vs FFC: ↓ GCT, ↑ posterior GRI and posterior GRF • 45˚ CUT: PFC vs FFC: ↔ posterior braking GRI and posterior GRF		
Graham Smith et al. (20)	12 male sports students (football or rugby)	Mod505	• PFC vs FFC: ↑ peak HBF, peak VBF, peak knee extensor moments • ↑ HBF related to greater knee flexor moments (r = -0.659, p = 0.02, r^2 = 43.4%)		↑ PFC peak HBF (r = -0.674, p = 0.016, r^2 = 45.4%)

Dos'Santos et al. (16)	(21 professional rugby and 19 collegiate athletes) (23.0 ± 2.9 years; 88.05 ± 12.86 kg;: 1.82 ± 0.07 m)	PP Mod505		Mod505 left: PFC peak HBF (r = -0.337, r^2 = 0.114, p < 0.05) HBF ratio (r = 0.429, r^2 = 0.184, p < 0.05) Fast vs slow (Mod505 left) ↓ HBF ratio (p = 0.006, ES = -1.50), ↑ PFC HBF (p = 0.027, ES = 1.08)
Nedergaard et al. (62)	10 male soccer players (21 ± 3 years; 73 ± 6 kg; 1.78 ± 0.1 m)	PP V cut 135˚	• ↑ average trunk decelerations in IPS and PFC vs FFC • PFC vs FFC: ↑ peak joint angular velocities in knee and ankle • GCT ↑ from IPS foot contact to PFC to FFC	
Greig (21)	10 male professional soccer players (24.7 ± 4.4 years; 77.1 ± 8.3 kg;)	PP 180˚ COD 3.5 m approach	PFC vs FFC: ↑ max knee flexion angle and ROM	
Kimura & Sakurai (45)	Seven male university basketball (19.4 ± 0.7 years; 1.80 ± 0.07 m, 77.1 ± 8.3 kg;)	PP 60˚ cut 5.83 ± 0.32 $m.s^{-1}$	PFC vs FFC**:** ↓ GCT ↑ posterior impulse	
Jones et al. (40)	18 female soccer players (21.6 ± 4.3 years, 1.67 ± 0.07 m and 60.3 ± 6.3 kg)	PP 505		Stronger vs weaker (ECC knee extensor - (3.80 ± 0.39 vs 2.93 ± 0.24 Nm·kg^{-1}, ES = 2.69) • ↓ completion times (p < 0.0001, ES = 2.09), ↑ approach greater velocity (p = 0.015, ES =*1.27*), ↑ reductions in velocity during the PFC (ES =-0.94) • ↑ peak HGRF, average HGRF, hip flexor moments (ES =0.95–1.23)

Key: ↑ = Greater; ↓ = Lower; PP = Pre-planned; UP = Unplanned; COD = Change of direction; mod505 = modified 505; PFC = Penultimate foot contact; FFC = Final foot contact; HBF = Horizontal braking force; GCT = Ground contact time; HBI = Horizontal braking impulse; VBF = Vertical braking force; WA = Weight acceptance; GRF = Ground reaction force; GRI = Ground reaction impulse; IPS = Ipsilateral; HGRF = Horizontal ground reaction force; ECC = Eccentric; ROM = Range of motion; IPS = Ipsilateral foot contact; pKAM = peak Knee abduction moment; ES = Effect size

Note: Associative injury risk factor studies have been performed under controlled approach velocities (42, 43, 44), and most studies published have examined anticipated pre-planned CODs with linear approach running. Differences in knee joint loading have been reported at greater velocities (45, 90) and during unanticipated conditions (50). Furthermore, athletes perform CODs from curved and oblique running in sport (92). Therefore, some of the aforementioned studies may lack ecological validity to the scenarios and actions of when ACL injuries occur during CODs, typically in unanticipated situations in the presence of opponents under high visual, spatial and temporal constraints (7, 59, 64).

Table 2 . Technical guidelines for the preparatory step during sharp cuts (blue line represents force vector)



Preparatory Step - initial contact (Image A)	Preparatory Step - weight acceptance (Image B and C)	Preparatory Step - transition to FFC (Image D and E)
• Lower COM to increase balance and stability. • Large COP to COM distance – achieved via anterior placement of foot (PFC) relative to posteriorly directed COM achieved via backward trunk lean. This strategy utilised to emphasise posteriorly directed force vector and to maximise HBF to reduce momentum (impulse = momentum relationship) (32, 40, 42-44) • Heel strike and slight ankle plantar flexion (32, 42). • Knee generally extended and slight hip flexion • Trunk and head facing forwards – or slight rotation towards intended direction of travel. for effective realignment into the new intended direction and earlier visual scanning of the situation (31).	• Foot rapidly rolls on to forefoot and keeps in contact to maximise braking impulse, and transitions into dorsi flexion (32, 42, 87) • Knee goes through great range of flexion (up to ~100˚) (21, 42) over a GCT of 0.15-0.40 s (influenced by entry velocity and angle of COD) (16, 25, 45, 62) • Simultaneous hip flexion to absorb loading through greater ROM compared to FFC - facilitates longer braking force application, thus impulse, resulting in a greater reduction in velocity (impulse = change in momentum) • Simultaneous hip and knee flexion lowers COM increasing balance and stability, and peak hip flexor, knee flexor and ankle plantar flexor moments typically occur during first 10-30% of PFC ground contact (42) • Knee should be correctly aligned with no knee valgus to reduce knee joint loading (27, 29) • Trunk continues to be upright/ leaning back – Continued posteriorly directly force vector • Head and trunk may slightly rotate towards direction of travel to facilitate effective realignment into the new intended direction and earlier visual scanning of the situation (31) • Typically absorbing GRF through sagittal plane which is safer and utilizes the hip and knee extensor musculature	• Hip and knee flexion is maintained in the transition period to allow optimal position in preparation for FFC. Max knee flexion typically occurs at the end of ground contact (42) • Trunk will remain upright or slightly forward lean in preparation for FFC – trunk may rotate towards direction of travel to facilitate optimal trunk lean strategy for FFC – push off phase (37, 67, 60) • Alternatively, athletes may decide to rotate their whole body during the flight phase between PFC and FFC to effectively align themselves into the new intended direction (26, 77) • COP in preparation for FFC to be planted in front of the body for push off into new intended direction

Note – Arms should be positioned close to the body to reduce whole body moment of inertia to facilitate quicker rotation. However, use of sports objects (i.e. rugby/American football ball, lacrosse stick, hockey stick) may impact on use of arms.

Key: COM = Center of mass; COM = Center of pressure; PFC = Penultimate foot contact;; PFC = Penultimate foot contact;; GRF = Ground reaction force;; ROM = Range of motion; HBF = Horizontal braking force; GCT = Ground contact time

Table 3. Six-week braking strategy technique modification training program

Week	COD Emphasis	Drills	Intensity (perceived speed)	Total Distance (m)	Number of Decelerations and CODs
Week 1	• Drills specific to deceleration phase, before adding turn and reacceleration • Submaximal/ pre-planned emphasising key aspects of technique • Progressive increase in COD angle and approach velocity	1. 8 x 5 m acceleration to deceleration 2. 6 x 5 m lateral shuffle to deceleration 3. 6 x 5 m acceleration to side steps (20-60˚) – 5 m exit to deceleration 4. 6 x 5 m acceleration to turns (135˚) – 5 m exit to deceleration	50-75%	190	26 and 12
Week 2		1. 8 x 5 m acceleration to deceleration 2. 6 x 5 m lateral shuffle to deceleration 3. 8 x 5 m acceleration to side steps (45-90˚) - 5 m exit to deceleration 4. 8 x 5 m acceleration to turns– 5 m exit to deceleration	75%+	230	30 and 16
Week 3	• Pre-planned drill performed maximally • Introduction of unanticipated generic stimuli (auditory or visual) • Unanticipated performed submaximally	1. 4 x 5 m acceleration to deceleration 2. 4 x 2.5-7.5m unanticipated decelerations – auditory stimuli 3. 4 x 2.5-7.5m unanticipated lateral decelerations – visual stimuli 4. 8 x 7.5 m acceleration to side steps (60-90˚) – 5 m exit to deceleration 5. 8 x 7.5 m acceleration to turns (135-180˚) – 5 m exit to deceleration	1. 100% 2. 50-75% 3. 50-75% 4. 100% 5. 100%	240-280	28 and 16
Week 4		1. 6 x 10 m acceleration to side steps (60- 90˚) - 5 m exit to deceleration 2. 6 x 2.5-12.5 m unanticipated decelerations – auditory stimuli 3. 6 x 10 m acceleration to turns (135-180˚) – 5 m exit to deceleration 4. 6 x unanticipated 5 m sidesteps (45-90˚) - coach pointing – 5 m exit 5. 6 x unanticipated clock face drill (5 m entry and 5 m exit) – auditory stimuli (coach shouts number corresponding to clock face) - decelerations and CODs of any angle	1. 100% 2. 75%+ 3. 100% 4. 75%+ 5. 75%+	315-375	24 and 24
Week 5	• Unanticipated drills performed maximally • Introduction of sport specific stimuli – opponent or ball	1. 8 x 2.5-15 m unanticipated decelerations – against an opponent* 2. 8 x 5 m unanticipated cuts (60- 90˚)* – against an opponent or ball - 5 m exit to deceleration 3. 8 x 2.5 - 10 m lateral shuffle mirror drill against an opponent* 4. 4 Modified L runs – anticipated - (5 m acceleration to 90˚ cut, 5 m acceleration to 180˚ turn – 5 m acceleration to 90˚ cut to 5 m exit to deceleration. (3 CODs and 1 deceleration per rep = 20 m per rep)	100%	200-360	20 and 28
Week 6		1. 8 x 2.5-15 5m unanticipated 180˚ turn –against an opponent* to deceleration 2. 8 x 10 m unanticipated COD – reacting to ball (60-180˚) – 5 m exit to deceleration 3. 8 x 2.5 - 10 m lateral shuffle mirror drill – against an opponent* 4. 4 Modified L runs – anticipated - (7.5 m acceleration to 90˚ cut, 7.5 m acceleration to 180˚ turn – 7.5 m acceleration to 90˚ cut –7.5 m exit to deceleration. (3 CODs and 1 deceleration per rep = 30 m per rep)	100%	280-460	20 and 36

Additional information:

1. 30-60 seconds' rest provided between 100% effort reps. 2 minutes' rest provide between exercises
2. All CODs and decelerations to be performed with the aim of modified braking strategy
3. Feedback to be provided to each player after each rep regarding braking strategy/ COD technique

Key: * = Alternate between leading and reacting / attacking and defending; COD = Change of direction; PFC = Penultimate foot contact