Sports Med (2018) 48:1799–1807
https://doi.org/10.1007/s40279-018-0931-3

REVIEW ARTICLE

Change-of-Direction Biomechanics: Is What's Best for Anterior Cruciate Ligament Injury Prevention Also Best for Performance?

Aaron S. Fox[1]

Published online: 2 May 2018

Abstract Change-of-direction maneuvers (e.g., side-step cutting) are an important aspect of performance in multi-directional sports, but these maneuvers are also associated with anterior cruciate ligament (ACL) injury. Despite this, the impact of biomechanics on ACL injury risk and performance is often examined in isolation. The purpose of this review was to examine the alignment between biomechanical recommendations for ACL injury prevention and performance with regard to change-of-direction maneuvers. Several studies linking change-of-direction biomechanics to both ACL injury risk and performance were examined. A degree of overlap was identified between biomechanical strategies that could both reduce ACL injury risk and enhance performance during change-of-direction maneuvers. A fore-foot footfall pattern along with trunk rotation and lateral flexion in the intended cutting direction were identified as biomechanical strategies that could both reduce potentially hazardous knee joint moments and enhance change-of-direction speed. Minimizing knee valgus during change-of-direction maneuvers may also reduce ACL injury risk, with this biomechanical strategy found to have no impact on performance. Certain biomechanical strategies proposed to reduce ACL injury risk were linked to reduced change-of-direction performance. A narrow foot placement and "soft" landings with greater knee flexion were identified as ACL injury prevention strategies that could have a negative impact on performance. The findings of this review emphasize the need to consider both ACL injury risk and performance when examining the biomechanics of change-of-direction maneuvers.

✉ Aaron S. Fox
aaron.f@deakin.edu.au

[1] Centre for Sports Research, School of Exercise and Nutrition Sciences, Deakin University, 75 Pigdons Road, Waurn Ponds, VIC 3216, Australia

Key Points

Change-of-direction maneuvers that utilize a fore-foot footfall pattern (i.e., toe landings) as well as trunk rotation and lateral flexion towards the cutting direction may both reduce anterior cruciate ligament (ACL) injury risk and enhance performance. ACL injury prevention programs that promote these movement strategies are likely to be well received and implemented by coaches and athletes because of this dual benefit.

Performing a change-of-direction maneuver with a narrow foot placement and with greater knee flexion or a "soft" landing has the potential to reduce ACL injury risk. Care must be taken when promoting these movement strategies within ACL injury prevention programs as they are also associated with reduced performance.

The relationship between ACL injury risk and change-of-direction performance must be considered when implementing injury prevention programs to ensure altered movement strategies are not being employed at the expense of performance.

1 Introduction

Change-of-direction maneuvers (e.g., side-step cutting) are frequently performed and are an important determinant of performance within multi-directional sports such as soccer, rugby, Australian Rules football, and netball [1–6]. These maneuvers are also associated with anterior cruciate ligament (ACL) injury [7–9]. Although related to both sports performance and ACL injury risk, these factors are often investigated in isolation when examining change-of-direction maneuvers. While some studies recognize that modification of technique for injury prevention can impact performance [10–13], this is not always acknowledged within studies examining ACL injury risk [14–19]. There is evidence to suggest that ACL injury prevention strategies do not improve change-of-direction performance [20]. Coach and athlete behavior in sport is driven by performance, therefore injury prevention strategies that have a dual benefit (i.e., performance enhancement and injury risk reduction) are more likely to be well-received and implemented [20]. However, how ACL injury prevention recommendations relate to change-of-direction performance recommendations, and vice versa, remains to be determined. Understanding the relationship between these two factors may assist in the design of more appropriate ACL injury prevention programs. The purpose of this review was to summarize the literature surrounding change-of-direction biomechanics relating to both ACL injury risk and task performance. Specifically, this review aims to examine the alignment between biomechanical recommendations for ACL injury prevention and performance with regard to change-of-direction maneuvers.

2 Characterizing Anterior Cruciate Ligament (ACL) Injury Risk versus Performance

2.1 ACL Injury Risk

Injuries to the ACL occur when forces applied to the ligament are greater than the loads it can withstand [21]. ACL injuries have been observed to occur with a forceful valgus collapse and tibial rotation with the knee in a relatively extended position [8, 22, 23]. Experimental studies support these observations, where knee valgus and internal rotation moments [24–27], reduced knee flexion [24, 28, 29], and large anterior tibial shear forces [30] have all been shown to increase ACL loads. ACL injury prevention strategies targeting biomechanical technique therefore revolve around minimizing the use of movement strategies that promote these ACL loads. “Dynamic valgus” postures and greater peak knee abduction moments have been identified as key factors linked to increased ACL injury risk [31]. Positions of “dynamic valgus” stem from knee abduction combined with hip adduction and internal rotation [31–33], all of which have been associated with peak knee moments during athletic tasks [11, 16, 34]. A more erect lower limb posture (i.e., reduced hip and knee flexion) reduces the capacity to attenuate and absorb forces at the knee [12, 15, 35]. Peak ACL strains have been shown to occur when knee flexion angles are lowest [29], with cadaveric data also showing a greater increase in ACL loads in response to external moments when knee flexion angles are reduced [28]. Increases in ACL strain and force have also been reported with internal tibial rotation motion and loads [24, 25]. Although external tibial rotation results in minimal increases in ACL strain and force [24, 25], rotation in this direction has also been observed during ACL injury [8]. A number of biomechanical factors have been linked to ACL loading or injury and are subsequently used to characterize potential injury risk within biomechanical studies. Given the link to ACL loading and injury risk, movement strategies that contribute to the presence of these biomechanical factors should be avoided when performing change-of-direction maneuvers.

2.2 Performance

Change-of-direction maneuvers in sports are often performed to evade an opponent during attacking play [1, 4]. Technique is considered an important aspect of change-of-direction performance [2], whereby the biomechanics of the athlete can impact the performance speed [10, 36–39] and deceptive qualities [4] of the maneuver. Biomechanical studies have tended to characterize performance by how quickly the athlete is able to complete certain parts of the movement [4] or the total time taken to complete the cutting movement (including the approach to and exit from the movement) [10, 36, 37]. Ground contact time during the step used to perform a change-of-direction maneuver is another performance indicator used across the biomechanical literature [36, 37]. Reduced ground contact time means athletes spend less time breaking and propelling themselves in the new direction, resulting in faster change-of-direction performance [37]. Studies have shown a negative correlation between ground contact and total cutting time [36, 37], highlighting that shorter ground contact times are associated with better overall cutting performance. In addition to speed, an element of deception will also benefit the athlete when a defender is present [4, 40]. Change-of-direction maneuvers that can be quickly performed while disguising the athlete’s intention may therefore give the greatest performance advantage [4].

3 Study Selection

Studies were identified for this review by searching online databases (SPORTDiscus, AMED, MEDLINE, and CINAHL) using a combination of relevant keywords. Articles were included for review if they performed biomechanical measurements of technique during a change-of-direction maneuver and attempted to link this to ACL injury risk factors or task performance. Following the initial search, the reference lists of included articles were examined for any further relevant studies. The following sections outline the findings of included studies relevant to specific aspects of change-of-direction technique and the subsequent biomechanical recommendations for ACL injury prevention versus performance.

4 Trunk Biomechanics

Proximal motion at the trunk appears to have a substantial role in modulating the loads experienced at the knee and potential ACL injury risk. Biomechanics of the trunk are frequently linked to the loads experienced at the knee during change-of-direction maneuvers [11, 12, 14, 15, 38, 41]. Lateral flexion of the trunk away from the intended change of direction has been linked to greater knee abduction moments [12, 14, 15, 38]. This relationship has been shown in both pre-planned and unanticipated 45° [14, 15] and pre-planned 90° [11] side-step cutting maneuvers. The relationship between lateral trunk flexion and frontal plane knee moments can be explained by a shift in the athlete's weight laterally with trunk lean, creating a laterally directed force vector [11]. This can increase the moment arm of the ground reaction force vector relative to the knee joint in the frontal plane, subsequently increasing the knee abduction moment [11, 12, 15]. This relationship is further supported by video analyses, where lateral torso flexion is a commonly observed biomechanical characteristic of ACL injury [23, 42]. Further, there is support for correcting this movement strategy as a means to reduce frontal plane knee loading. Simulations of side-step cutting show shifting the whole-body center of mass medially towards the intended cutting direction is an effective strategy for reducing knee abduction moments [41]. Further, following 6 weeks of technique modification training, a group of male athletes were able to perform both pre-planned and unplanned 45° side-step cuts with reduced lateral trunk flexion [12]. This more neutral torso position was associated with reduced peak knee abduction moments [12].

Rotation of the trunk away from the intended cutting direction has also been linked to greater knee loads, whereby this biomechanical strategy has been associated with larger internal rotation moments during a pre-planned 45° side-step cut [15]. Lateral flexion and rotation of the trunk in the intended cutting direction is therefore advocated as an appropriate biomechanical strategy for reducing ACL injury risk [11, 12, 14, 15]. This aligns with performance recommendations, whereby cutting time can be improved with rotation of the trunk [36] or by using a biomechanical strategy that promotes greater lateral trunk flexion [10] in the intended cutting direction. Rotation of the trunk in the transverse plane has been linked to performance times during side-step cutting [36]. Marshall et al. [36] examined performance of a 75° side step in male Gaelic hurling athletes. Performance was measured as "total cutting time," defined as the time taken to perform a 5-m approach to the side-step cut followed by a 5-m run to a finish line [36]. Individuals with greater rotation of the trunk toward the desired cutting direction during the maneuver recorded faster cutting times [36]. Trunk rotation was positively correlated with ankle plantar flexor power, hence it was hypothesized that those with a more rotated trunk were in a better body position to produce a greater power output about the ankle [36].

It is important to note that these biomechanical links to ACL injury risk factors and performance were identified under planned change-of-direction conditions [11, 15, 36] or where a consistent time to prepare the movement was maintained [14]. Change-of-direction maneuvers often require the athlete to react to a stimulus (e.g., an opposition player's movement; movement of play or the ball) [2]. Altered preparation time has been shown to impact the biomechanical strategy used during side-step cutting, particularly with regard to the trunk [38]. Mornieux et al. [38] examined the postural adaptations required to maintain performance during an unanticipated 45° side-step cutting maneuver, where the time available to prepare the maneuver progressively reduced. In the step before and during the change of direction, both trunk rotation and lateral flexion in the opposite direction to the cutting maneuver increased with reduced preparation time [38]. The greatest differences were observed for lateral trunk flexion; thus, it was concluded that this biomechanical strategy was the most relevant for maintaining performance of a cutting maneuver under unpredictable conditions [38]. The upright and more laterally flexed trunk position may also stem from the intended direction being unknown until later in the movement, resulting in an inability to quickly move the trunk towards this direction. While suited to performance, this biomechanical strategy resulted in higher knee abduction moments [38] and is also in direct conflict with ACL injury prevention recommendations [11, 12, 14, 15]. These findings highlight a potential trade-off between ACL injury risk and performance when preparation time is reduced. Given that change-of-direction maneuvers are commonly performed in response to a stimulus in unpredictable sporting environments [2, 5], it should be expected that athletes will encounter scenarios that involve this trade-off. Under such circumstances, avoidance of this altered trunk strategy would need to be compensated for by other preparatory adjustments to maintain change-of-direction performance during unpredictable conditions [38]. ACL injury prevention programs targeting trunk rotation and lateral flexion must therefore promote compensatory strategies to ensure performance is not sacrificed for injury prevention. Little evidence exists as to what these strategies may be, thus additional research on how to avoid hazardous trunk motion while maintaining performance during unpredictable change-of-direction scenarios is required [38].

5 Hip Biomechanics

Like with the trunk, the proximal motion of the hip can affect the loads experienced at the knee. Sagittal plane motions at the hip during change-of-direction maneuvers have been linked to biomechanical factors associated with increased ACL loading or injury risk [10, 16, 34]. Greater hip flexion at initial contact and during the early stance phase of cutting maneuvers has been associated with larger knee abduction moments [16, 34]. A link between hip flexion and ACL injury risk is also supported by video analyses, where ACL injuries were found to occur with greater hip flexion immediately after landing compared with relevant control (i.e., non-injurious) landings [42]. It is not clear why the relationship between hip flexion and frontal plane knee moments exists. Selective activation of medial muscle groups in the lower limb has been identified as a viable strategy for minimizing knee abduction moments during side-step cutting [43, 44]. McLean et al. [34] suggested excessive hip flexion at initial contact may limit the capacity of these medial muscles to adequately support against knee abduction loads, but their study design did not allow for this hypothesis to be tested. Kipp et al. [16] offered further explanation as to why this potential relationship exists, suggesting that early rapid hip flexion may rotate the trunk forward and away from the landing leg, resulting in the center of pressure shifting in an anterior and lateral direction. This shift in the center of pressure away from the body increases the moment arm of the ground reaction force relative to the knee. While hip flexion early in stance has been associated with increased frontal plane knee moments, Kipp et al. [16] found that greater hip flexion across the entire stance phase of the cutting maneuver was associated with reduced knee internal rotation moments. Again, the relationship between these variables is not entirely clear. However, it was proposed that active flexion across the cutting maneuver may better enable the major muscle groups crossing the knee to absorb energy and more effectively minimize knee moments in other planes of motion (i.e., transverse plane) [16].

Transverse plane hip motion has also been linked to frontal plane knee moments during changes of direction [10, 17, 34, 45]. Specifically, greater internal rotation at the hip has been associated with larger knee abduction moments during a number of different cutting maneuvers [17, 34, 45]. Excessive hip internal rotation can induce a position of "dynamic valgus," whereby the knee shifts medially while the foot remains in contact with the ground [33]. This may alter the moment arm in the frontal plane about the knee, as the center of pressure is directed laterally away from the knee joint [17]. In contrast, Havens and Sigward [10] found that smaller degrees of hip internal rotation were associated with larger frontal plane knee loads during a 90° side-step cut. It was suggested that this difference stemmed from the smaller cutting angle (i.e., 45°) used in previous studies [17, 34].

In contrast to ACL injury risk, no relationship between hip motion and side-step cutting performance appears to have been found. However, Havens and Sigward [10] showed that greater hip power generation in the sagittal plane and hip extensor moments were predictive of shorter completion times during a 45° side-step cut. It was suggested that the hip extensors were mostly responsible for generating power during the deceleration of the cutting maneuver, hence their relation to performance [10]. The greater redirection demands of a 90° versus 45° side-step cut (i.e., cutting to a greater angle) were proposed to alter the biomechanical strategies relevant to performance [10]. Hip power generation in the frontal rather than the sagittal plane was found to predict shorter completion times during 90° side-step cuts [10]. The change-of-direction angle may therefore be a factor to consider when evaluating both biomechanical motions that may contribute to ACL injury risk or influence performance. It appears that changes in hip motion (particularly in the sagittal and transverse plane) could be relevant targets for reducing ACL injury risk while avoiding performance decrements. However, it would be a requirement that these changes do not negatively affect power generation at the hip to avoid sacrificing performance for injury prevention.

6 Knee Biomechanics

The biomechanics of the knee have a direct influence on the strain and force experienced by the ACL and thus have a substantial impact on injury risk. A "dynamic valgus" posture stemming from combined knee abduction, hip adduction, and hip internal rotation is acknowledged as a key indicator of ACL injury risk [31]. Knee valgus has also been associated with other biomechanical characteristics linked to increased ACL loads and injury risk during change-of-direction maneuvers [11, 13, 34, 45]. Specifically, numerous studies have linked greater knee valgus to increased peak knee abduction moments during a range of side-step cutting tasks [11, 13, 34, 45]. Kristianslund et al. [13] found alignment of the lower limb had the greatest impact on modulating knee abduction moments during side-step cutting. Improving frontal plane knee alignment during change-of-direction maneuvers has subsequently been proposed as a viable strategy for reducing ACL injury risk [11, 13, 34, 45].

Few studies have investigated the relationship between knee valgus and cutting performance, but Marshall et al. [36] found no relationship during a 75° side-step cut. Similarly, large peak knee abduction moments have been linked to higher ACL loads and injury risk [24–27, 31] without any recognized relationship with change-of-direction performance [10]. Given this, improving valgus alignment and minimizing frontal plane knee moments during side-step cutting may be an appropriate strategy for reducing ACL injury risk without sacrificing performance. However, certain biomechanical strategies highlighted as appropriate for reducing knee abduction moments could be both detrimental (e.g., foot placement, see Sect. 8.3) or positive (e.g., lateral directing of the trunk in the intended cutting direction, see Sect. 4) for performance. Promoting biomechanical strategies that achieve the latter may therefore be more attractive for coaches within ACL injury prevention programs.

In contrast to knee biomechanics in the frontal plane, sagittal plane knee biomechanics may have a modulating effect on side-step cutting performance. Altered sagittal plane knee biomechanics may have the potential to increase ground contact time and subsequently reduce performance during change-of-direction maneuvers. Dai et al. [39] examined the influence of instruction on side-step cutting performance, whereby athletes were asked to perform a 45° side-step cut as quickly as possible under normal conditions, as well as while attempting to "land with greater knee flexion." Stance time (i.e., ground contact time) increased when athletes were instructed to "land with greater knee flexion" [39]. Greater peak knee flexion was observed during these performances, with this increase in range of motion likely contributing to the increase in stance time [39]. Increasing knee flexion is a common target within ACL injury prevention programs [46–51]; however, simply instructing athletes to perform cutting maneuvers with greater knee flexion may be detrimental to performance. Other forms of instructions that promote knee flexion without the reduction in speed, or other modifications to technique that enhance change-of-direction speed in conjunction with increased knee flexion, are likely required.

7 Ankle Biomechanics

Recent work has begun to establish a relationship between ankle biomechanics and the potential for ACL injury risk. In particular, the impact of footfall pattern (i.e., rear foot vs. fore foot) on side-step cutting biomechanics has been investigated [13, 18, 19]. These patterns are directly related to the magnitude of ankle plantarflexion versus dorsiflexion present at initial contact of the cutting maneuver. The use of a fore-foot strike pattern has been suggested to reduce the loads placed on the knee joint and ACL [13, 18, 19]. Yoshida et al. [18] found knee valgus angles tended to be smaller during 60° side-step cuts performed with a fore-foot pattern. Similarly, Kristianslund et al. [13] found "toe landings" (i.e., a fore-foot pattern) were associated with reduced peak knee abduction moments during side-step cutting. The toe landing appeared to help athletes better align their lower extremity to reduce the moment arm of the ground reaction force in the frontal plane [13]. These findings were further supported by a study showing that athletes who used a habitual rear-foot strike pattern during unplanned side-step cuts absorb greater work and power through the knee, resulting in elevated peak knee abduction moments [19].

Ankle biomechanics have also been linked to change-of-direction performance [10, 36]. Greater ankle plantarflexion moments have been associated with improved performance during both 45° [10] and 75° [36] side-step cuts. Further, Marshall et al. [36] found that greater peak ankle power was also associated with faster times to complete the 75° side-step cutting task examined. Concentric power at the ankle was the strongest predictor of cutting performance within this study [36]. This is not surprising, as concentric ankle power is an important performance indicator in other explosive movements such as sprinting [52] and vertical jumping [53]. The ankle has been suggested to play an important role in the production of horizontal velocity after the center of mass is in front of the center of pressure [52]. Power and force generation by the ankle is likely of great importance during the final stages of change-of-direction maneuvers, where the center of mass is ahead of the plant foot in the intended new direction. In the aforementioned study by Donnelly et al. [19], greater peak ankle plantarflexion moments were observed in those who utilized a fore-foot footfall pattern. A fore-foot footfall pattern during side-step cutting may therefore protect against ACL injury risk by improving frontal plane knee alignment and reducing knee abduction moments while also providing a performance advantage by increasing the ankle plantarflexion moment.

Certain individuals shift to a fore-foot footfall pattern at higher running speeds during straight-line running [54]. Currently there is little evidence to suggest that approach speed modulates footfall pattern during side-step cutting, with no differences in speed observed between rear- and fore-foot patterns [19]. However, the speeds at which these cuts were performed ($\sim$ 4.3 m·s^{-1}) [19] did not reach the speed at which most individuals shifted to a fore-foot footfall pattern during straight-line running (5.1–6.2 m·s^{-1}) [54]. It may be that further increases in approach speed during side-step cutting may result in individuals naturally shifting to a fore-foot footfall pattern. Higher approach speeds are related to increased performance but result in higher knee loads [55], whereas a fore-foot footfall pattern is related to both increased performance and reduced knee loads [19]. A natural shift to a fore-foot footfall pattern may counteract the increase in knee loads associated with higher approach speeds and subsequently present a protective effect against ACL injuries with increased performance. However, further work is required to establish whether this relationship between higher approach speeds and footfall pattern exists.

8 Other Factors

8.1 Overall Technique

The overall technique with which an athlete performs a change of direction may be associated with knee biomechanics and subsequent ACL injury risk. Trewartha et al. [56] investigated the effect of overall change-of-direction technique on peak knee joint moments in a group of male rugby players. Knee joint moments were compared between two techniques: a side step (i.e., changing direction in one step by planting a leg to the side of the body to push off in the opposite direction [4]) and split step (i.e., landing from a small jump on both feet and using the foot opposite the intended direction to initiate the change of direction [4]). While no overall group differences were identified, individuals who were most successful in distributing the ground reaction forces between both limbs during the split step were found to reduce peak frontal and transverse plane knee moments when using this technique [56]. Effective use of this technique may therefore reduce potentially hazardous knee loading and minimize ACL injury risk. The split step may also be a viable change-of-direction technique from a performance perspective. Bradshaw et al. [4] examined the deceptive power and speed of this technique in addition to the side step and shuffle techniques (a series of small "side steps" with minimal lateral trunk displacement followed by a final larger side step to change direction). With regard to deceptive power, athletes viewing videos of the three techniques were slower and less accurate in their guesses of the cutting direction when viewing the split step compared with the shuffle and side step [4]. While no differences were found in the entry and exit times across the techniques, the split step incurred a greater foot plant preparation time (i.e., longer time to prepare the movement) [4]. The split-step change-of-direction technique may present both injury risk reduction and performance benefits, but this may only be relevant to certain athletes in certain situations. The potential reduction of ACL injury risk relies on the athlete being proficient in distributing the loads between limbs [56], and performance benefits may only be seen in one-on-one situations where time constraints on movement preparation are less restrictive [4].

8.2 Approach Speed and Cutting Angle

The speed at which a player approaches a change-of-direction maneuver, as well as the resultant angle at which the change of direction is performed, have also been linked to peak knee abduction moments and thus potential ACL injury risk [13, 55]. Side-step cuts performed with a faster approach speed and larger cutting angle (i.e., a sharper cut) require greater impulse to perform the movement [13]. This is reflected in the higher ground reaction forces and subsequent higher knee abduction moments observed with side-step cuts performed with these characteristics [13]. It is important to note that an increase in knee loading and potential for injury risk could be expected with faster performance of change-of-direction maneuvers, particularly when approach speed is increased [13, 55]. Given its relation to performance, reduction of approach speed should not be considered a viable ACL injury prevention strategy [13]. Despite this, commonly used instructional methods within injury prevention programs could inadvertently alter athletes' approach speeds during change-of-direction maneuvers. ACL injury prevention programs often use feedback protocols that emphasize a "soft" landing style, generally achieved by increasing flexion at lower limb joints or minimizing landing noise [46–51]. While this may reduce the load placed on the ACL during change-of-direction maneuvers, the strategies athletes use to achieve this landing style may have detrimental effects on performance. Reduced approach and take-off speeds and increased ground contact times have been observed during side-step cuts performed by athletes attempting to land "softly" or with greater knee flexion [39]. The performance decrements were suggested to stem from the athlete's attempts to meet the landing technique instructions [39]. These findings highlight how athletes can sacrifice performance to meet the instructional demands set out by an injury prevention program. Whether this is a conscious or sub-conscious decision by athletes, care must be taken when using such instructions within injury prevention programs given how they can impact performance.

8.3 Foot Placement

Foot placement is a biomechanical characteristic commonly linked to knee moments during side-step cutting [11, 13, 15]. A wider foot placement is characterized by the planted cutting foot being placed further from the body or center of mass [13, 15] and can occur with greater hip abduction [17]. In contrast, a narrow or close foot placement refers to the planted cutting foot being placed closer to the body [15]. A wide foot placement technique was imposed on athletes in the study by Dempsey et al. [12], which resulted in significantly greater peak knee abduction and internal rotation moments [12]. Similarly, Kristianslund et al. [13] found that "wider" side-step cuts (i.e., foot placed further away from the body's center of mass) resulted in larger peak knee abduction moments during a handball-specific side-step cutting task. Jones et al. [11] found that lateral leg plant distance was linked to peak knee abduction moments during pre-planned 90° side-step cuts. Greater separation of the medial–lateral center of pressure with respect to the center of mass, indicative of a wider foot placement, has also been associated with larger knee abduction moments during 45° side-step cuts [10]. Further studies have linked greater hip abduction to larger knee abduction moments during various change-of-direction maneuvers [10, 17]. A wider foot placement results in the center of pressure moving laterally, altering the ground reaction forces moment arm relative to the knee [17]. This creates a large moment arm for the vertical force at the distal tibia and subsequently increases the knee abduction moment [13, 17].

While a wider foot placement has the potential to increase knee loads and potential ACL injury risk, it may provide performance benefits during change-of-direction maneuvers. Shorter completion times have been linked to a larger medial–lateral distance from the center of pressure to the center of mass (i.e., a wider foot placement) during 45° side-step cuts [10]. The greater medial–lateral center of pressure to center of mass separation distance was suggested to allow for acceleration and momentum generation towards the new direction [10]. While shifting foot placement closer to the whole-body center of mass (i.e., a more narrow foot placement) has been advocated as a biomechanical strategy for reducing knee abduction moments [12, 15], this strategy may be detrimental to performance. During changes of direction, medial ground reaction forces are generated by increasing lateral foot plant distance to accelerate the body in the intended direction [11]. This presents a direct conflict between what is presented as an appropriate biomechanical strategy for reducing ACL injury risk and performance. Despite this apparent conflict, Dempsey et al. [12] found no change in performance characteristics of a side-step cutting maneuver when athletes shifted to a narrower foot placement. Together, these findings stress the importance of monitoring change-of-direction performance with alterations to foot placement to ensure this biomechanical strategy is not employed at the expense of performance. If this is the case, additional adjustments to the athlete's technique may be required to counteract the performance decrements associated with this narrower foot placement.

9 Limitations and Recommendations

This review was potentially limited by how performance was characterized across the biomechanical literature. For the most part, "performance" was inferred using total cutting times during tasks that incorporated approaches to and exits from the cutting maneuver [10, 36, 37]. Straight-line running speed could contribute to better performance of these maneuvers in such studies, which could affect the observed relationships between biomechanical cutting technique and "performance." Further, these studies did not examine performance in unanticipated scenarios [10, 36, 37]. The ability to change direction in response to stimulus is an important aspect of change-of-direction performance in competitive environments [2]. Investigating change-of-direction biomechanics in unanticipated scenarios is an important aspect of understanding performance and should therefore be considered in future work.

Several studies in this review focused on relating the biomechanics of change-of-direction maneuvers to ACL injury risk or performance in isolation [14–19, 36, 37]. The findings of this review highlight how this approach can result in conflicting recommendations with regard to these two important areas. Whether the target is ACL injury prevention or performance, altering change-of-direction biomechanics will likely affect both these areas and hence must be considered together. Future studies should incorporate appropriate experimental or in silico methods to test the interaction between ACL injury risk and performance during change-of-direction maneuvers, rather than focusing on one factor in isolation.

10 Conclusions

Overall, the alignment of biomechanical recommendations for ACL injury prevention and change-of-direction performance is mixed. A degree of overlap was identified between biomechanical strategies that are recommended for both reducing ACL injury risk and enhancing change-of-direction performance. A fore-foot footfall pattern as well as trunk rotation and lateral flexion in the intended cutting direction were identified as biomechanical strategies that both reduce ACL injury risk and enhance performance. Minimizing knee valgus and knee abduction moments during change-of-direction maneuvers may also reduce ACL injury risk without affecting performance. However, the biomechanical strategies used to minimize frontal plane knee moments must be considered as the various approaches promoted may have differing effects on altering performance. In contrast, certain biomechanical strategies proposed to reduce ACL injury risk, such as a narrow foot placement and "soft" landings with greater knee flexion, must be carefully considered given their potential detrimental effect on change-of-direction performance. Where these biomechanical strategies are promoted for ACL injury prevention, additional adjustments should be made to the cutting technique to avoid any associated performance decrements. This review emphasizes the importance of considering both ACL injury risk and performance when examining change-of-direction maneuvers. Injury prevention programs that target the biomechanics of change-of-direction maneuvers must also consider how any changes could impact performance to ensure one is not emphasized over the other.

Compliance with Ethical Standards

Funding No external sources of funding were used to assist in the preparation of this article.

Conflicts of interest Aaron Fox has no conflicts of interest relevant to the content of this review.

References

1. Fox A, Spittle M, Otago L, Saunders N. Offensive agility techniques performed during international netball competition. Int J Sports Sci Coach. 2014;9(3):543–52.
2. Sheppard J, Young W. Agility literature review: classifications, training and testing. J Sports Sci. 2006;24(9):919–32.
3. Brughelli M, Cronin J, Levin G, Chaouachi A. Understanding change of direction ability in sport. Sports Med. 2008;38(12):1045–63.
4. Bradshaw RJ, Young WB, Russel A, Burge P. Comparison of offensive agility techniques in Australian Rules football. J Sci Med Sport. 2011;14(1):65–9.
5. Gabbett T, Benton D. Reactive agility of rugby league players. J Sci Med Sport. 2009;12(1):212–4.
6. Terblanche E, Venter R. The effect of backward training on the speed, agility and power in netball players. S Afr J Res Sport Phys Educ. 2009;31(2):135–45.
7. Myklebust G, Maehlum S, Holm I, Bahr R. A prospective cohort study of anterior cruciate ligament injuries in elite Norwegian team handball. Scand J Med Sci Sports. 1998;8(3):149–53.
8. Olsen OE, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. Am J Sports Med. 2004;32(4):1002–12.
9. Cochrane J, Lloyd D, Buttfield A, Seward H, McGivern J. Characteristics of anterior cruciate ligament injuries in Australian football. J Sci Med Sport. 2007;10(2):96–104.
10. Havens KL, Sigward SM. Cutting mechanics: relation to performance and anterior cruciate ligament injury risk. Med Sci Sports Exerc. 2015;47(4):818–24.
11. Jones PA, Herrington LC, Graham-Smith P. Technique determinants of knee joint loads during cutting in female soccer players. Hum Mov Sci. 2015;42:203–11.
12. Dempsey AR, Lloyd DG, Elliott BC, Steele JR, Munro BJ. Changing sidestep cutting technique reduces knee valgus loading. Am J Sports Med. 2009;37(11):2194–200.
13. Kristianslund E, Faul O, Bahr R, Myklebust G, Krosshaug T. Sidestep cutting technique and knee abduction loading: implications for ACL prevention exercises. Br J Sports Med. 2014;48(9):779–83.
14. Jamison ST, Pan X, Chaudhari AMW. Knee moments during run-to-cut maneuvers are associated with lateral trunk positioning. J Biomech. 2012;45(11):1881–5.
15. Dempsey AR, Lloyd DG, Elliott BC, Steele JR, Munro BJ, Russo KA. The effect of technique change on knee loads during sidestep cutting. Med Sci Sports Exerc. 2007;39(10):1765–73.
16. Kipp K, McLean SG, Palmieri-Smith RM. Patterns of hip flexion motion predict frontal and transverse plane knee torques during a single-leg land-and-cut maneuver. Clin Biomech. 2011;26(5):504–8.
17. Sigward SM, Powers CM. Loading characteristics of females exhibiting excessive valgus moments during cutting. Clin Biomech. 2007;22(7):827–33.
18. Yoshida N, Kunugi S, Mashimo S, Okuma Y, Masunari A, Miyazaki S, et al. Effect of forefoot strike on lower extremity muscle activity and knee joint angle during cutting in female team handball players. Sports Med Open. 2016;2:32.
19. Donnelly CJ, Chinnasee C, Weir G, Sasimontonkul S, Alderson J. Joint dynamics of rear- and fore-foot unplanned sidestepping. J Sci Med Sport. 2017;20(1):32–7.
20. Vescovi JD, VanHeest JL. Effects of an anterior cruciate ligament injury prevention program on performance in adolescent female soccer players. Scand J Med Sci Sports. 2010;20(3):394–402.
21. Lloyd DG. Rationale for training programs to reduce anterior cruciate ligament injuries in Australian football. J Orthop Sports Phys Ther. 2001;31(11):645–54.
22. Krosshaug T, Nakamae A, Boden BP, Engebretsen L, Smith G, Slauterback JR, et al. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. Am J Sports Med. 2007;35(3):359–67.
23. Hewett TE, Torg JS, Boden BP. Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: lateral trunk and knee abduction motion are combined components of the injury mechanism. Br J Sports Med. 2009;43(6):417–22.
24. Markolf KL, Burchfield DM, Shapiro MM, Shephard MF, Finerman GAM, Slauterback JL. Combined knee loading states that generate high anterior cruciate ligament forces. J Orthop Res. 1995;13(6):930–5.

25. Oh YK, Lipps DB, Ashton-Miller JA, Wojtys EM. What strains the anterior cruciate ligament during a pivot landing? Am J Sports Med. 2012;40(3):574–83.
26. Shin CS, Chaudhari AM, Andriacchi TP. Valgus plus internal rotation moments increase anterior cruciate ligament strain more than either alone. Med Sci Sports Exerc. 2011;43(8):1484–91.
27. Withrow TJ, Huston LJ, Wojtys EM, Ashton-Miller JA. The effect of an impulsive knee valgus moment on in vitro relative ACL strain during a simulated jump landing. Clin Biomech. 2006;21(9):977–83.
28. Mizuno K, Andrish JT, van den Bogert AJ, McLean SG. Gender dimorphic ACL strain in response to combined dynamic 3D knee joint loading: implications for ACL injury risk. Knee. 2009;16(6):432–40.
29. Taylor KA, Terry ME, Utturkar GM, Spritzer CE, Queen RM, Irribarra LA, et al. Measurement of in vivo anterior cruciate ligament strain during dynamic jump landing. J Biomech. 2011;44(3):365–71.
30. DeMorat G, Weinhold P, Blackburn T, Chudik S, Garrett W Jr. Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. Am J Sports Med. 2004;32(2):477–83.
31. Hewett TE, Myer GD, Ford KR, Heidt RS Jr, Colosimo AJ, McLean SG, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. Am J Sports Med. 2005;33(4):492–501.
32. Donnelly CJ, Elliott BC, Ackland TR, Doyle TLA, Beiser TF, Finch CF, et al. An anterior cruciate ligament injury prevention framework: incorporating the recent evidence. Res Sports Med. 2012;20(3–4):239–62.
33. Powers CM. The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. J Orthop Sports Phys Ther. 2010;40(2):42–51.
34. McLean SG, Huang X, van den Bogert AJ. Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: implications for ACL injury. Clin Biomech. 2005;20(8):863–70.
35. Brown TN, Palmieri-Smith RM, McLean SG. Knee kinematics during single- and double-legged jump landings following six weeks of neuromuscular training. J Athl Train. 2010;45(5):530.
36. Marshall BM, Franklyn-Miller AD, King EA, Moran KA, Strike SC, Falvey ÉC. Biomechanical factors associated with time to complete a change of direction cutting maneuver. J Strength Cond Res. 2014;28(10):2845–51.
37. Dos'Santos T, Thomas C, Jones PA, Comfort P. Mechanical determinants of faster change of direction speed performance in male athletes. J Strength Cond Res. 2017;31(3):696–705.
38. Mornieux G, Gehring D, Fürst P, Gollhofer A. Anticipatory postural adjustments during cutting manoeuvres in football and their consequences for knee injury risk. J Sports Sci. 2014;32(13):1255–62.
39. Dai B, Garrett WE, Queen RM, Gross MT, Padua DA, Yu B. The effects of 2 landing techniques on knee kinematics, kinetics, and performance during stop-jump and side-cutting tasks. Am J Sports Med. 2015;43(2):466–74.
40. Jackson RC, Warren S, Abernethy B. Anticipation skill and susceptibility to deceptive movement. Acta Psychol. 2006;123(3):355–71.
41. Donnelly CJ, Lloyd DG, Elliott BC, Reinbolt JA. Optimizing whole-body kinematics to minimize valgus knee loading during sidestepping: implications for ACL injury risk. J Biomech. 2012;45(8):1491–7.
42. Boden BP, Dean GS, Feagin JA Jr, Garrett WE Jr. Mechanisms of anterior cruciate ligament injury. Orthopedics. 2000;23(6):573–8.
43. Besier TF, Lloyd DG, Ackland TR. Muscle activation strategies at the knee during running and cutting maneuvers. Med Sci Sports Exerc. 2003;35(1):119–27.
44. Lloyd DG, Buchanan TS. Strategies of muscular support of varus and valgus isometric loads at the human knee. J Biomech. 2001;34(10):1257–67.
45. Sigward SM, Cesar GM, Havens KL. Predictors of frontal plane knee moments during side-step cutting to 45 and 110 degrees in men and women: implications for anterior cruciate ligament injury. Clin J Sport Med. 2015;25(6):529–34.
46. Donnelly CJ, Elliott BC, Doyle TLA, Finch CF, Dempsey AR, Lloyd DG. Changes in knee joint biomechanics following balance and technique training and a season of Australian football. Br J Sports Med. 2012;46(13):917–22.
47. Herman DC, Oñate JA, Weinhold PS, Guskiewicz KM, Garrett WE, Yu B, et al. The effects of feedback with and without strength training on lower extremity biomechanics. Am J Sports Med. 2009;37(7):1301–8.
48. Myer GD, Stroube BW, DiCesare CA, Brent JL, Ford KR, Heidt RS, et al. Augmented feedback supports skill transfer and reduces high-risk injury landing mechanics: a double-blind, randomized controlled laboratory study. Am J Sports Med. 2013;41(3):669–77.
49. Petersen W, Braun C, Bock W, Schmidt K, Weimann A, Drescher W, et al. A controlled prospective case control study of a prevention training program in female team handball players: the German experience. Arch Orthop Trauma Surg. 2005;125(9):614–21.
50. Stroube BW, Myer GD, Brent JL, Ford KR, Heidt RS Jr, Hewett TE. Effects of task-specific augmented feedback on deficit modification during performance of the tuck-jump exercise. J Sport Rehabil. 2013;22(1):7–18.
51. Mandelbaum BR, Silvers HJ, Watanabe DS, Knarr JF, Thomas SD, Griffin LY, et al. Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. Am J Sports Med. 2005;33(7):1003–10.
52. Debaere S, Delecluse C, Aerenhouts D, Hagman F, Jonkers I. From block clearance to sprint running: characteristics underlying an effective transition. J Sports Sci. 2013;31(2):137–49.
53. Vanezis A, Lees A. A biomechanical analysis of good and poor performers of the vertical jump. Ergonomics. 2005;48(11–14):1594–603.
54. Breine B, Malcolm P, Frederick EC, De Clercq D. Relationship between running speed and initial foot contact patterns. Med Sci Sports Exerc. 2014;46(8):1595–603.
55. Vanrenterghem J, Venables E, Pataky T, Robinson MA. The effect of running speed on knee mechanical loading in females during side cutting. J Biomech. 2012;45(14):2444–9.
56. Trewartha G, Munro BJ, Steele JR. Split-step vs. side-step: what is the difference in lower limb loads? J Biomech. 2007;40(S2):S238.