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Different visual stimuli affect muscle activation at the knee during sidestepping

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ABSTRACT

Increasing knee stability via appropriate muscle activation could reduce anterior cruciate ligament (ACL) injury risk during unplanned sidestepping. High-level athletes may activate their knee muscles differently from low-level athletes when responding to quasi-game realistic versus non game-realistic stimuli. Eleven high-level and 10 low-level soccer players responded to a non game-realistic arrow-planned condition (AP), a quasi game-realistic one-defender scenario (1DS) and two-defender scenario (2DS), and an arrow-unplanned condition (AUNP), that imposed increasing time constraints to sidestep. Activation from eight knee muscles during sidestepping was measured during pre-contact and weight-acceptance. Knee flexor-extensor co-activation ratios were established. Muscle activation levels increased by approximately 27% solely in the 1DS in both sidestepping phases. In the 2DS, the shift from a flexor dominant co-activation strategy in pre-contact toward extensor dominance in weight-acceptance commenced earlier for the high-level players. Quasi game-realistic information allowed for anticipatory increases in knee muscle activation regardless of expertise levels but only when the time demands to respond were low (1DS). High-level players were better at interpreting complex game-realistic information (2DS) to activate their knee extensors earlier in preparation for single-leg landing during weight-acceptance.

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Introduction

Non-contact anterior cruciate ligament (ACL) injuries often occur when athletes perform unplanned sidestepping (SS) (Cochrane, Lloyd, Buttfield, Seward, & McGivern, 2007; Olsen, Myklebust, Engebretsen, & Bahr, 2004). Laboratory studies have shown that the knee is loaded via a combination of flexion, valgus and internal rotation moments during the stance phase of SS (Besier, Lloyd, Cochrane, & Ackland, 2001b). This combination loads the ACL the most (Kim et al., 2015; Markolf et al., 1995) but large knee valgus moments and postures have been reported to independently entail the highest risk of ACL injuries during dynamic movements (Boden, Dean, Feagin, & Garrett, 2000; Hewett et al., 2005). Counteracting knee-valgus moments during SS seems crucial in preventing non-contact ACL injuries (Dempsey, Lloyd, Elliott, Steele, & Munro, 2009).

Knee flexors and extensors, when appropriately activated, can reduce loading on the joint and thereby reduce ACL loading (Besier, Lloyd, & Ackland, 2003; Sturnieks, Besier, & Lloyd, 2011). While quadriceps activation during knee extension causes anterior tibial translation that strains the ACL (Draganich & Vahey, 1990), co-activation of the hamstrings and quadriceps near full knee extension can reduce valgus-varus and internal-external rotation moments and thereby reduce ligament loading (Buchannan, Kim, & Lloyd, 1996; Lloyd & Buchannan, 2001). Besier et al. (2003) reported that planned SS performed under minimal time constraints had large knee-valgus moments that were supported by greater activation of the medial versus lateral knee muscles compared with running. The medial knee muscles have moment arms that produce varus moments to counter external valgus moments. Unplanned SS; whereby participants sidestepped as quickly as possible in the direction indicated by the illumination of a light-based stimulus; resulted in further increases in knee-valgus moments that were supported with equal instead of unequal co-activation of the medial and lateral muscle groups, and an increase in total muscle activation (TMA) compared with planned SS (Besier et al., 2003). Knee muscle activation patterns evidently vary when different time constraints are imposed by changes to the visual environment.

The level of game-realism when presenting visual stimuli to impose time and space constraints during SS could affect the performer's body reorientation strategies. For example, footballers were able to adjust their step widths to sidestep with less contralateral trunk flexion when evading video projections of opponents but were unable to do so when responding to light-based stimuli (Lee, Lloyd, Lay, Bourke, & Alderson, 2016). Sidestepping strategies are further differentiated by athletes' skill levels. High-level athletes sidestepped with 40% less knee valgus moments than low-level athletes when responding to complex quasi game-realistic visual stimuli (Lee, Lloyd, Lay, Bourke, & Alderson, 2013). It could be possible that neuromuscular responses such as muscle activation patterns may also be further differentiated between high-level and low-level

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athletes when unplanned SS is performed not just in response to light-based visual stimuli but quasi-game-realistic stimuli.

This study investigated the 1) knee muscle activation patterns that may support valgus loading and 2) whether high-level versus low-level athletes would exhibit different knee muscle activation patterns when they sidestepped in response to various visual stimuli. The quasi game-realistic one-defender scenario (1DS) and two-defender scenario (2DS), and traditionally employed arrow-planned condition (AP) and arrow-unplanned condition (AUNP) were previously described by Lee, Bourke, Alderson, Lloyd, and Lay (2010); (2013); 2016). The two-dimensional AP and AUNP imposed limited visuospatial constraints, while the three-dimensional 1DS and 2DS imposed visuospatial constraints via depth changes of the converging defender(s). The 1DS was intended to impose less visuospatial constraints than the 2DS while the time constraints imposed by the stimuli conditions increased in the following order: AP, 1DS, 2DS and AUNP.

Methods

The methods in this study are similar to those of our previous studies (Lee et al., 2013, 2016) except for the type and number of data sets that were successfully collected and analysed from that pool of participants.

Participants

Participants were 11 high-level (mean age 24.9 ± 3.9 yr, height 179.0 ± 7.0 cm, mass 73.8 ± 10.3 kg) and 10 low-level (mean age 23.7 ± 2.8 yrs, height 181.1 ± 6.0 cm, mass 70.2 ± 5.7 kg) male soccer players. Participants had no history of serious lower limb injuries such as fractures, dislocations or ligament tears above grade three. The high-level players competed semi-professionally (playing experience 13.7 ± 4.2 yrs). The low-level players competed in the amateur league (playing experience 6.1 ± 1.5 yrs). Informed consent was obtained from all participants prior to data collection and in compliance with the procedures of the Human Research Ethics Committee at The University of Western Australia.

Experimental procedures

Briefly, participants performed sidestep and crossover cuts on their dominant leg in response to the AP, 1DS, 2DS and AUNP (see Lee et al., 2013, 2016). For clarity, a right leg dominant participant would sidestep to the left or crossover to the right depending on the travel direction indicated by the stimuli (Figure 1). The arrow conditions would point either left or right when presented. The 1DS and 2DS required participants to read the projected defenders and avoid them by SS into the "open space". The 2DS imposed the highest level of visuospatial constraints followed by the 1DS. The arrow conditions imposed minimal visuospatial constraints. The temporal constraints imposed by the stimuli conditions increased from the AP, 1DS, 2DSto the AUNP.

Participants ran between two infra-red timing gates at 4.5 ± 0.5 m.s^{-1} and cut at 45° ± 10° in all stimuli conditions. The approach velocity of 4.5 ± 0.5 m.s^{-1} was chosen because Cochrane et al. (2007) reported that most non-contact ACL injuries occurred when footballers were running between 3 to 5 m.s^{-1} prior to the onset of injuries and replicating this speed in the laboratory increases the experimental protocol's ecological validity. Only sidesteps were analysed. The crossovers served to deter participants from pre-empting the type of maneuver and direction of imposed travel. Participants had to sidestep and crossover three times in response to each of the four stimuli conditions that were presented in a randomised manner, totalling 24 trials.

A Stereoscopic System presented the stimuli conditions (Lee et al., 2010). A 1.2 × 1.2 m AMTI force plate (Advanced Mechanical Technology Inc., Watertown, MA) served as a standardised location for foot-contact of the dominant push-off foot during the cutting tasks. Pre-contact and weight-acceptance of the sidestep were identified from ground reaction force data. Pre-contact was the 50 ms period prior to foot-contact and provides insight into the pre-programmed nature of muscle activation at the knee. Weight-acceptance was the period between initial foot-contact to the first trough in the unfiltered vertical ground-reaction force. Knee-valgus moments were analysed in weight-acceptance as they were reported to peak in this phase, suggesting a period of high ACL injury risk (Besier et al., 2003, 2001b).

A NoraxonTelemyosystem (Noraxon USA, Scottsdale, AZ) collected EMG activity from bipolar Ag/AgCl surface electrodes (ClearTraceTM; ConMed Corporation, Utica, NY, USA) that were attached to the skin above eight muscles of the dominant leg: semimembranosus (SM), biceps femoris (BF), medial gastrocnemius (MG), lateral gastrocnemius (LG), vastusmedialis (VM), rectus femoris (RF), vastuslateralis (VL), and tensor fascia latae (TFL). The skin was shaved, exfoliated and cleaned with ethanol swabs. Electrodes were placed 20 mm apart over the mid bellies and in line with the fibres of the selected muscles. A ground electrode was placed over the head of the greater trochanter (Konrad, 2005).

The raw EMG data were band-pass filtered between 30 Hz to 500 Hz using a zero-lag, 4th order, Butterworth filter and then full wave rectified. Linear envelopes were created using a zero-lag, 4th order, Butterworth filter, with a cut-off frequency of 6 Hz. EMG data collected during the different SS conditions were normalised to the peak muscle activation measured from the AP. Normalizing EMG data to a functional task can minimise inter-subject variability (Branch, Hunter, & Donath, 1989).

Muscle co-activation was assessed to examine the muscle activation strategies employed during SS and has three different characteristics: the 1) TMA of agonists and antagonists, 2) ratio of agonist to antagonist activation, and 3) determination of which agonists or antagonists were dominant co-contractors (Heiden, Lloyd, & Ackland, 2009; Sturnieks et al., 2011). These characteristics can be described using TMA and the directed co-activation ratio. The muscles were first grouped according to their potential to produce flexion, extension, valgus or varus moments at the knee, i.e., flexor muscles: SM, BF, MG and LG; extensor muscles: VM, RF, VL and TFL; varus/medial muscles: SM, VM and MG; valgus/lateral muscles: BF, VL, LG. The RF and TFL were excluded from the varus and valgus groupings due to the RF's midline insertion into the patella and the minimal contribution by the TFL in

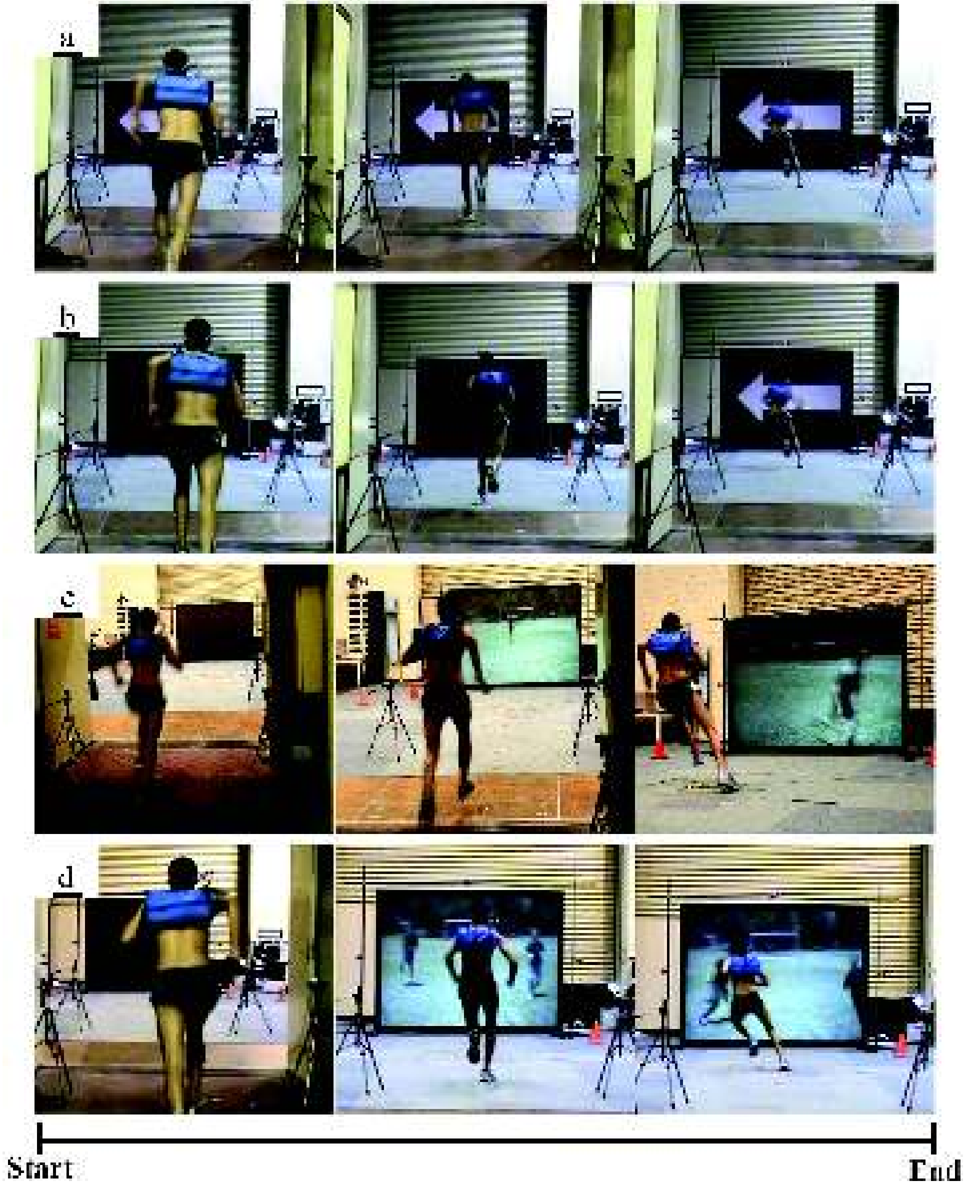

Figure 1. A right leg dominant participant running and sidestepping to the left in response to the different stimuli conditions: (A) AP, (B) AUNP, (C) 1DS, and (D) 2DS. Reprinted from "Effects of different stimuli on postures and knee moments during sidestepping," by Marcus JC Lee, David G Lloyd, Brendan S Lay, Paul D Bourke and Jacqueline A Alderson, 2013, *Medicine and Science in Sports and Exercise*, 45(9), 1740–1748. Copyright (2013) by Wolters Kluwer Health, Inc. Reprinted with permission.

supporting valgus-varus moments (Lloyd & Buchannan, 2001). TMA; the sum of each muscle's normalised EMG; was calculated to reflect the level of support by the knee musculature. Two directed co-activation ratios were established: 1) flexor-extensor and 2) varus-valgus, and were calculated;

Equation 1; if mean EMG for agonist > antagonist, directed co-activation ratio = 1 – (mean EMG for antagonist/agonist), and;

Equation 2; if mean EMG for antagonist > agonist, directed co-activation ratio = (mean EMG for agonist/antagonist) – 1

The flexor and varus muscle groups were chosen as agonists. The extensor and valgus muscle groups were chosen as antagonists. If the agonists were more activated than their antagonists, the directed co-activation ratio would be positive, and vice versa. Equal activation levels of agonists and antagonists would yield a directed co-activation ratio equal to zero (Heiden et al., 2009).

Mean TMA and directed co-activation ratios in pre-contact and weight-acceptance were averaged over three sidesteps performed in the respective stimuli conditions. Using SPSS 16.0 (SPSS Inc., Chicago, IL), within and between group mean differences were ascertained using a 4 × 2 (stimuli x skill level) mixed-design ANOVA ($p < 0.05$). Differences approaching significance were $0.05 < p < 0.08$ and were reported with effect sizes whereby d = (Mean 1-Mean 2)/SDpooled; SDpooled = $\sqrt{((SD1^2 + SD2^2)/2)}$. Effect sizes were small when $d \leq 0.2$, moderate when $0.3 \leq d \leq 0.5$ and large when $d \geq 0.8$. Significant main and interaction effects were assessed using post-hoc tests with Sidak corrections.

Results

In pre-contact (Table 1), TMA during SS was affected by the type of stimuli conditions presented. TMA in the different stimuli conditions increased in the following order: AP, AUNP, 2DS, 1DS. Post-hoc testing revealed that TMA in the 1DS was 27% higher than AUNP (p < 0.01). The flexors were dominant across all stimuli conditions (positive flexor-extensor directed co-activation ratios). Post-hoc testing revealed that SS in the AP resulted in more flexor activation compared with the 1DS (p < 0.01), 2DS (p < 0.05) and AUNP (p < 0.025).

In pre-contact, stimuli type interacted with skill for the flexor-extensor directed co-activation ratios. For the high-level players, flexor-extensor directed co-activation ratio was most flexor dominant in the AP, and increasingly moved toward being extensor dominant in the following order: 1DS, AUNP, 2DS. The low-level players' flexor-extensor directed co-activation ratio was also most flexor dominant in the AP, but increasingly moved toward being extensor dominant in a different order: 2DS, 1DS, AUNP. Post-hoc testing revealed that the flexor-extensor directed co-activation ratio of the low-level players (0.62 ± 0.22) in the 2DS tended to be more flexor dominant than the high-level players (0.41 ± 0.28) (p < 0.06) and the effect was large (d = 0.83).

In weight-acceptance (Table 2), TMA in the different stimuli conditions increased in the following order: AUNP, AP, 2DS, 1DS. Post-hoc tests revealed that TMA in the 1DS was 18% higher than AUNP (p < 0. 01). A flexor dominant flexor-extensor directed co-activation ratio remained in the AP, whereas the extensors dominated across the remaining conditions. Post-hoc tests revealed that the flexors were more dominant in the AP than AUNP (p < 0.001) and exhibited a similar trend with a moderate to large effect (d = 0.63) when compared with the 2DS (p < 0.08). Additionally, the flexor-extensor directed co-activation ratio in the AUNP tended to be more extensor dominant with a moderate to large effect (d = 0.61) than the 1DS (p < 0.07).

Table 1. The pre-contact total muscle activation, flexor-extensor directed co-activation ratio, and varus-valgus directed co-activation ratio across different stimuli and skill conditions.

Stimulus	Total muscle activation Mean (SD)	Flexor-extensor directed co-activation ratio Mean (SD)	Varus-valgus directed co-activation ratio Mean (SD)
AP	2.08 (0.70)	0.67 (0.13)	0.30 (0.21)
1DS	2.37 (0.65)	0.51 (0.23)	0.25 (0.20)
2DS	2.12 (0.78)	0.51 (0.25)	0.27 (0.25)
AUNP	1.87 (0.77)	0.42 (0.39)	0.24 (0.30)
Stimulus effect *p* value	0.001*	0.002*	0.484
Post hoc results	1DS > AUNP*	AP > 1DS*	
		AP > 2DS*	
		AP > AUNP*	
Skill Level			
High-level (HL)	2.06 (0.76)	0.54 (0.20)	0.28 (0.24)
Low-level (LL)	2.17 (0.69)	0.52 (0.28)	0.25 (0.25)
Skill effect *p* value	0.702	0.864	0.714
Post hoc results		HL < LL#	
Stimulus x Skill *p* value	0.355	0.042*	0.246

* represents significant differences at $p < 0.05$.
# represents approaching significantly different at $0.05 < p < 0.08$.

Table 2. The weight-acceptance total muscle activation, flexor-extensor directed co-activation ratio, and varus-valgus directed co-activation ratio across different stimuli and skill conditions.

Stimulus	Total muscle activation Mean (SD)	Flexor-extensor directed co-activation ratio Mean (SD)	Varus-valgus directed co-activation ratio Mean (SD)
AP	2.84 (0.74)	0.01 (0.28)	0.10 (0.21)
1DS	3.06 (0.68)	−0.11 (0.29)	0.10 (0.24)
2DS	2.82 (0.79)	−0.18 (0.32)	0.06 (0.23)
AUNP	2.59 (0.85)	−0.27 (0.23)	0.11 (0.26)
Stimulus effect *p* value	0.015*	< 0.001*	0.749
Post hoc results	1DS > AUNP*	AP > 2DS#	
		AP > AUNP*	
		1DS > AUNP#	
Skill Level			
High-level (HL)	2.82 (0.84)	−0.17 (0.29)	0.11 (0.25)
Low-level (LL)	2.84 (0.69)	−0.10 (0.27)	0.08 (0.23)
Skill effect *p* value	0.942	0.474	0.752
Post hoc results			
Stimulus x Skill *p* value	0.341	0.080	0.279

* represents significant differences at $p < 0.05$.
# represents approaching significantly different at $0.05 < p < 0.08$.

Discussion

Knee muscle activation can support external knee loading and reduce ACL strain (Buchannan et al., 1996; Lloyd, Buchannan, & Besier, 2005). This study investigated the 1) knee muscle activation patterns that may support valgus loading and 2) whether high-level versus low-level athletes would exhibit different knee muscle activation patterns when they sidestepped in response to various visual stimuli.

TMA increase was the lowest in the AUNP, higher in the AP and 2DS, and highest in the 1DS. Sidestepping in the AUNP may entail the highest risk of ACL injury as there is no increase in knee muscle activation for additional support even though knee-valgus moments have been reported to be the highest in the AUNP compared with the defender scenarios and AP (Lee et al., 2013). This assertion takes into account that the current participants made up 70% of the participants in those studies. The highest TMA increase in the 1DS compared with the other stimuli conditions was surprising as the 1DS neither imposed the highest time constraints to sidestep (AUNP) nor was it the most complex quasi game-realistic visual stimuli to interpret (2DS). Perhaps while game-realistic visual information provided by the 1DS enabled participants to anticipate and increase TMA compared with SS in the AP, there could be a threshold affect between the 1DS and the more difficult AUNP and 2DS, whereby exceeding a timing threshold precluded an anticipated increase in knee TMA. Future research should seek to further unravel the visuomotor processes involved that contribute to this threshold and how athletes can read difficult visual information faster, to enable earlier anticipation and appropriate selection of activation patterns.

There was no change in the co-activation patterns of the medial-lateral knee muscles across stimuli conditions. In both phases of the sidestep, the varus muscle group was dominant across all the stimuli conditions. These results contradict what Besier et al. (2003) reported whereby greater medial/varus knee muscle activation was adopted during planned compared with unplanned SS. This discrepancy highlights the potential effect of the increased approach velocity of

4.5 ms^{-1} adopted in this study compared with 3.0 ms^{-1} in the study by Besier et al. (2003) and needs to be investigated further.

The knee flexors were dominant at the end of terminal swing in pre-contact to eccentrically slow rapid knee extension (Novacheck, 1998) and may reduce ACL loading in weight-acceptance. During weight-acceptance, the extensors activate eccentrically to slow knee flexion and facilitate extension for push-off (Novacheck, 1998). Eccentric quadriceps contraction at extended knee angles during landing may induce anterior tibial translation and strain the ACL (McConkey, 1986), but can be countered by co-activation of the hamstrings (McNair & Marshall, 1994).

Compared with planned SS, the higher timing demands in the reactive stimuli conditions reduced knee flexor dominance as evidenced in the smaller positive flexor-extensor directed co-activation ratios during pre-contact and greater negative ratios during weight-acceptance. The flexors were most dominant in the AP, less dominant in the defender scenarios and least dominant in the AUNP. This reinforces that SS in the AUNP has the highest potential for ACL strain and injury (Besier et al., 2003; Besier, Lloyd, Cochrane, & Ackland, 2001a) as high knee loadings as previously reported (Lee et al., 2013) may not be met with increased TMA for support. This risk is exacerbated by increased activation of the extensors in weight-acceptance, which may induce anterior tibial draw and further strain the ACL.

Skill level appeared to effect activation patterns. The high-level players tended to have a greater extensor dominant directed co-activation ratio in pre-contact, in the 2DS, than their lower-level counterparts. Regardless of skill, flexor dominance in pre-contact shifted towards extensor dominance in weight-acceptance in all stimuli conditions. At extended knee angles, the quadriceps can cause tibial anterior draw and potentially load the ACL (Lloyd & Buchannan, 1996). However, activating these muscles can stabilise the knee against varus and valgus moments, potentially lowering ACL loading (Lloyd et al., 2005). Elevated quadriceps activation prior to landing has been reported to reduce ACL strain upon landing (Hashemi et al., 2010). The activation strategy adopted by the high-level players in the 2DS may have reduced ACL loading.

The greater difficulty to sidestep in the 2DS compared with the 1DS allowed for the muscle activation patterns of high-level players to be differentiated from the low-level players. The increased difficulty imposed by the AUNP compared with the AP did not allow for such differentiation. Compared with low-level players, high-level players have been reported to moderate the potential for ACL loading in the 2DS by decreasing hip abduction and knee-valgus moments (Lee et al., 2013). These experimental outcomes highlight two notions. First, the use of generic instead of quasi game-realistic stimuli to investigate visual-perceptual-motor skills such as SS may mask certain aspects of the relationship between visual-perception and movement mechanics. Second, a high-level of game-realistic stimulus complexity (2DS) was required to discriminate the SS biomechanics between high- and low-level players. Skilled athletes may be at less risk of sustaining ACL injuries when SS in other complex sport situations.

Differences in the coupling between the perception of visual information and relevant motor action are not only related to performance but injury risk (Weinhandl et al., 2013). Although a substantial body of literature discusses how the motor component of SS associates with ACL injury risk (Hewett, Lindenfeld, Ricobene, & Noyes, 1999; McLean, Neal, Myers, & Walters, 1999), much less is known about the visual-perceptual contribution. The current findings, together with our recent findings (Lee et al., 2013, 2016), illustrate the effects that visual information has on SS biomechanics in both generic and quasi game-realistic environments. Studying both the visual-perceptual and motor parameters that contribute to either safe or unsafe sidestepping could present scientists and clinicians with more holistic understandings of the mechanisms that contribute to non-contact ACL injuries.

A limitation of the current findings is that knee valgus moments and by extension ACL injury risk were not measured within the scope of this study, but rather inferred from previous studies (Lee et al., 2013, 2016) whereby 70% of those participants were the participants in the current study. Another limitation is that the altered activation patterns may not be driven by the biomechanics of the knee, but by the hip and ankle. There are biarticular muscles that cross the knee, which have roles at the hip and ankle. However, previous research found that knee loading and postures directly dictated the activation of biarticular muscles (Lloyd & Buchannan, 1996, 2001).

Conclusion

This study provides new insights into the effect of visual information/stimuli on SS neuromuscular biomechanics. Imposing quasi game-realistic temporal and spatial constraints via 3D stimuli to investigate SS addresses both the visual-perceptual and motor components of SS, and may improve our understanding of the causes of ACL injury. The knee muscle activation patterns of the high-level players in the 2DS suggest the potential existence of a visual-perceptual-motor strategy that has been reported to reduce knee loading and injury risk during SS (Hashemi et al., 2010).

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Disclosure statement

No potential conflict of interest was reported by the authors. AQ3

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