Effects of Different Visual Stimuli on Postures and Knee Moments during Sidestepping

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ABSTRACT

LEE, M. J. C., D. G. LLOYD, B. S. LAY, P. D. BOURKE, and J. A. ALDERSON. Effects of Different Visual Stimuli on Postures and Knee Moments during Sidestepping. *Med. Sci. Sports Exerc.*, Vol. 45, No. 9, pp. 1740–1748, 2013. **Purpose**: Evasive sidestepping during sports commonly results in noncontact anterior cruciate ligament injuries. Sidestepping in response to different simple visual stimuli has been studied previously but never investigated using quasi–game-realistic visual conditions. We compared the biomechanics of high-level and low-level soccer players when sidestepping in response to projected, three-dimensional defender(s) and the traditionally used planned and unplanned arrow stimuli. **Methods**: A three-dimensional motion analysis system captured the trunk and lower limb kinematics and ground reaction forces of 15 high-level and 15 low-level soccer players sidestepping in response to a one-defender scenario (1DS), two-defender scenario (2DS), arrow-planned condition (AP), and arrow-unplanned condition (AUNP). The temporal constraints imposed by the stimuli conditions resulted in increasing difficulty from AP, 1DS, 2DS, to AUNP. Selected joint kinematics and three-dimensional knee moments during the weight-acceptance phase of sidestepping were analyzed. **Results**: Hip external rotation at initial foot contact was smaller when participants sidestepped in response to the projected defenders versus arrow conditions. Hip abduction was smallest in the AP, moderate in the defender scenarios, and largest in the AUNP. Peak knee valgus moments were 25% larger in the defender scenarios and 70% larger in the AUNP compared with the AP. High-level players exhibited decreased hip abduction and knee valgus moments in the 2DS compared with the low-level players. **Conclusions**: Compared with the arrow conditions, sidestepping in response to the defender(s) resulted in different postures and knee moments, which further differentiated between high-level and low-level players in the complex 2DS. These findings highlight the effects of stimuli realism and complexity on the visual–perceptual–motor skill of sidestepping, which has implications for anterior cruciate ligament injury prevention. **Key Words:** THREE-DIMENSIONAL BIOMECHANICS, ANTERIOR CRUCIATE LIGAMENT, INJURY, CUTTING, BODY REORIENTATION

Injuries to the anterior cruciate ligament (ACL) are serious and costly to treat, with most requiring surgical treatment followed by lengthy periods of rehabilitation (19). Common in team sports (12,34,36), ACL injury rates seem to have remained constant (3). Typically, ACL injuries are classified as either contact or noncontact. The latter contributes 50%–80% of all injuries, predominantly during sidestepping (12,36) in sports that require evasion (12,34). Laboratory studies have shown that a combination of flexion, valgus, and internal rotation moments are applied to the knee joint during the stance phase of sidestepping (6), which could strain the ACL (29). Video-based observations of ACL injuries during sidestepping have also shown that the rupture is characterized by knee valgus collapse (12,36) and internal rotation (12). Furthermore, peak knee valgus moments during landing tasks were found to be a good predictor of subsequent ACL injury (21). Consequently, the aforementioned knee kinetics during sidestepping has been the focus of various studies into key postures and movements associated with ACL injuries (6,10,32).

Several sidestepping body postures have been associated with ACL injury. Most ACL injuries occur soon after initial foot contact, when the knee is near full extension (24,30,31,36). From interviews and analyses of videos documenting injuries, postures such as "apparent large" knee valgus angles, external tibial rotation (36), hip flexion (24), hip internal rotation, hip abduction, trunk lateral flexion, foot pronation, and foot external rotation (22) have been observed during sidesteps that resulted in ACL injury. Laboratory-based studies have corroborated these findings, whereby similar trunk, hip, and knee sidestepping postures were related to large knee valgus (16,31) and internal rotation moments during stance phase (16). Although these laboratory studies have been important in understanding the key joint postures, movements, and moments that are amenable to change for ACL injury

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prevention, most injuries occur when athletes sidestep to evade opponents under high temporal and visuospatial demands. (24,36). As such, it may be important to study sidestepping in a laboratory setting that mimics the competition environment to better understand how the maneuver is performed and identify key factors involved in ACL injuries.

During basketball (24) and handball (36) competitions, most sidestepping-related ACL injuries were reported to occur when athletes were in offense and had their visual attention focused on either the scoring target (basket rim or goals) or a defensive opponent(s). A person's visual perception is sensitive to varying environmental demands and visual information could alter locomotive strategies adopted for changing directions (37). Opponents and/or scoring targets in the visual field could affect an athlete's perception of the amount of time and space available for sidestepping. This may compromise postural preparation and sidestep execution, consequently increasing the risk of injury. With this in mind, early efforts to investigate reactive sidestepping in a laboratory setting used either variation in the timing of a light stimulus (4,5) or a mannequin (32) to represent an opposing player to mimic game-based time (4,5) and space (32) constraints, respectively. These studies showed that sidestepping under increased time and space constraints affected body postures and increased knee valgus and internal rotation moments. Recently, Fedie et al. (18) also reported increased knee flexion and knee valgus moments when athletes caught or passed a ball during sidestepping. Collectively, the inclusion of some game characteristics in laboratory protocols seems to elicit joint postures and knee moment profiles that are important biomechanical factors related to ACL injuries.

Visual–perceptual skill is important for successful task performance across different domains. In sport, the study of visual–perceptual skill has primarily focused on expert and novice differences in using visual cues to facilitate appropriate anticipatory responses (39). More recent research showed that experts were only able to use pertinent visual information to enhance their visual–perceptual–motor task performance when the environment was "game realistic" (17). No differences between experts and novices are usually found when visual stimuli are not sport and context specific (1). Recalling the work of Besier et al. (4,5) and McLean et al. (32), the use of non–game-realistic visual stimuli in those studies may not adequately promote expert and novice differences in sidestepping and the associated links between perception and the risk of ACL injury.

The two aims of this study were 1) to investigate the biomechanics of soccer players when they sidestepped in response to different types of visual stimuli and 2) to examine if the types of visual stimuli affected the sidestepping biomechanics of players with different skill levels. The quasi–game-realistic stimuli were three-dimensional video projections of defensive opponent(s), consisting of a one-defender scenario (1DS) and a two-defender scenario (2DS) that have been previously described (25). Sidesteps performed to avoid the defender(s) in these scenarios were further compared with those performed in response to an arrow-planned condition (AP) and arrow-unplanned condition (AUNP). These two-dimensional directional arrows were used to elicit planned and unplanned sidestepping in previous research (4,5,15). Furthermore, the two-dimensional AP and AUNP imposed limited visuospatial constraints, whereas the three-dimensional 1DS and 2DS imposed visuospatial constraints via depth changes of the converging defender(s), with the 1DS inferred to pose less visuospatial constraints than the 2DS. The temporal constraints imposed by the stimuli conditions increased in difficulty in the following order: AP, 1DS, 2DS, and AUNP. It was therefore hypothesized that there would be increased hip extension, abduction and internal rotation, and lateral trunk flexion (contralateral to the sidestep direction) at initial foot contact with increasing temporal constraints imposed by the varying stimuli. These postures were reportedly associated with ACL injury (22,24,31,36). In addition, from the findings of our previous research (6), it was hypothesized that knee valgus and internal rotation moments would be greater in the 2DS and AUNP compared with the 1DS and AP because of the increased visuospatial and temporal constraints imposed by these stimuli. Finally, it was hypothesized that compared with low-level players, high-level players would exhibit safer joint postures and lower knee moments in response to the 1DS and 2DS because of their ability to use advanced visual cues to increase their time and space to perform sidestepping.

METHODS

Participants. Participants were 15 high-level (mean ± SD; age = 23.1 ± 3.9 yr, height = 180 ± 1 cm, mass = 73.6 ± 10.3 kg) and 15 low-level (mean ± SD; age = 22.5 ± 3.8 yr, height = 179.9 ± 6.8 cm, mass = 71.2 ± 7.0 kg) male soccer players consisting of midfielders and forwards. The high-level players competed semiprofessionally and had a mean playing experience of 13.5 ± 3.7 yr, whereas the low-level players competed in the amateur league and had a mean playing experience of 7.5 ± 1.3 yr. All participants had no history of serious lower limb injuries and were competent in performing all sporting maneuvers tested. Previous research comparing planned and unplanned sidestepping (5) revealed effect sizes of approximately 0.8. Using this value in a power analysis of a 4 × 2 (stimuli × skill) mixed-design ANOVA, a minimum of 12 subjects were necessary to achieve a statistical power of 0.8 and $P < 0.05$. All procedures were approved by the Human Research Ethics Committee at The University of Western Australia (UWA), and all participants provided their informed written consent before data were collected.

Experimental procedures. The participants performed either a running sidestep cut (4–6,10–12,15,16,31,32) or a crossover cut (4–6,11,12) in response to four different visual stimuli. Each stimulus required participants to either sidestep cut in one direction or crossover cut in the opposite direction. Both maneuvers were performed off the preferred dominant leg, which was self-selected by the participants

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during practice trials. For clarity, depending on the direction of travel indicated by the stimuli, a right leg dominant participant would sidestep to the left and crossover cut to the right. Although only the sidestepping trials were analyzed, the crossover cuts served to prevent the participants from preempting the direction of travel and type of maneuver. Participants were required to successfully perform three of each maneuver in response to four visual stimuli, totaling 24 trials.

The four visual stimuli consisted of two quasi–game-realistic conditions and two direction-arrow conditions. These were randomly presented on a large screen (Fig. 1) using a customized stereoscopic system (25). The timings of stimuli presentation were determined for each participant during familiarization and will be described later. The quasi–game-realistic 1DS and 2DS visual stimuli were created with the three-dimensional stereoscopic filming and projection techniques described previously (25). The 1DS (Fig. 1C) featured a defensive opponent converging on the approaching participant before changing directions. The participant's task was to cut in the opposite direction to the opponent. To prevent participants from becoming familiar to the 1DS, every filmed trial was unique, featuring the opponent wearing different attire and changing directions to either the left or the right side of the participant. The 2DS (Fig. 1D) featured two defensive opponents, one on either side of the participant's straight line of gaze, who converged on the approaching participant. As the participant approached the force plate, defender 1 who is on the participant's right would perform a 45° cut toward the participant, simulating a tackle. At the same instant, defender 2 who is on the participant's left

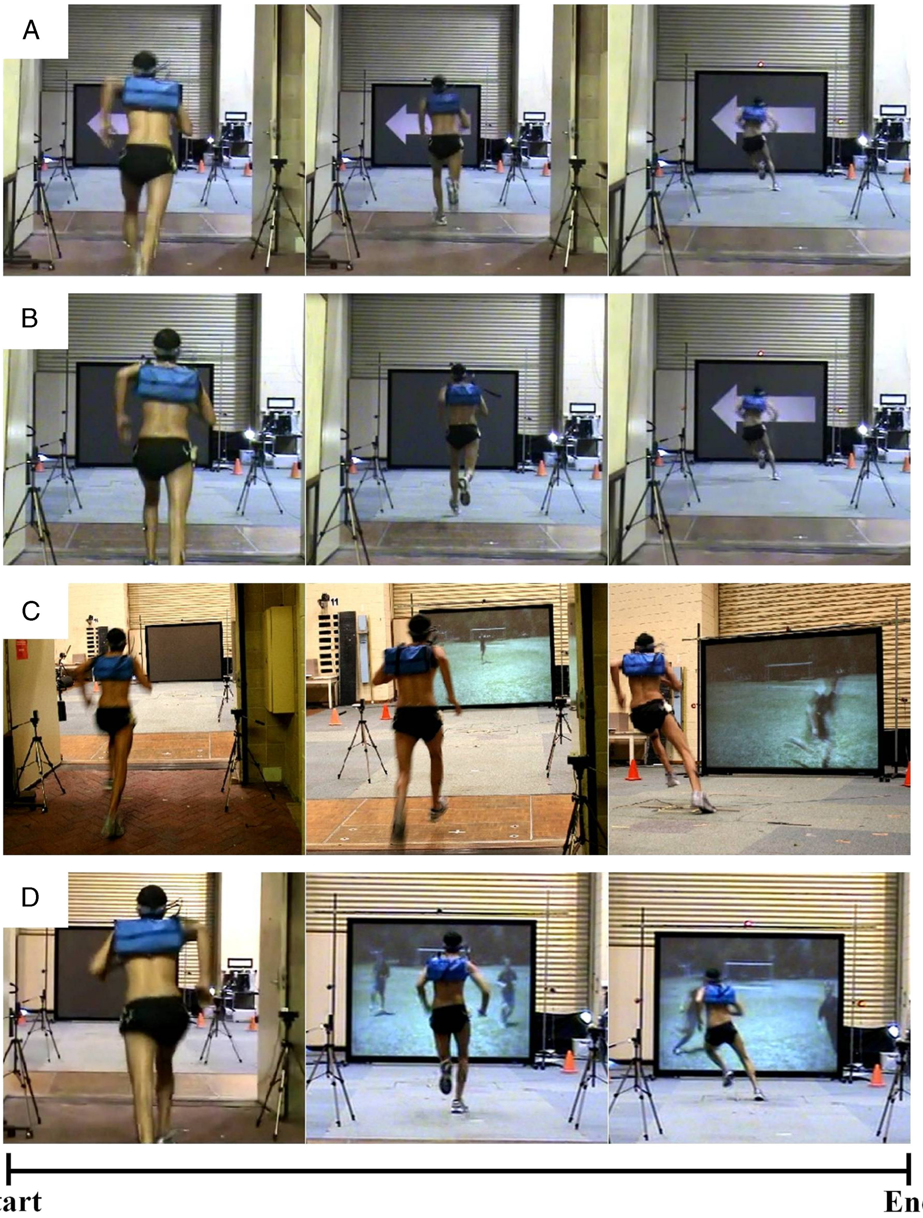

FIGURE 1—A right leg dominant participant running and sidestepping to the left in response to the different stimuli conditions: (A) AP, (B) AUNP, (C) 1DS, and (D) 2DS.

would initiate a 90°cut to the right, moving behind defender one. In this example, participants were required to cut to the left to avoid getting "tackled" by defender 1 and into the "space" previously occupied by defender 2. The defender movement directions were mirrored in the trials where a cut to the right was required. The 2DS was developed in consultation with two semiprofessional level soccer coaches and players from an amateur soccer club. Similar to the 1DS, each filmed trial had the defenders wearing different attire and switch starting positions to prevent the participants from becoming familiar with the 2DS.

The two direction-arrow conditions (AP and AUNP) were similar to the planned and unplanned light-based stimuli previously used by our group (4,5,11,15). The arrow in the AP (Fig. 1A) was presented on the screen before the participants starting the approach run and informed them of the required maneuver and travel direction. The AUNP (Fig. 1B) featured an arrow that only appeared when the participant was approximately one step from the force plate, providing minimal time for preparation and execution of the cutting task.

The various visual stimuli posed different levels of visuospatial and temporal constraints. The 1DS and 2DS were three-dimensional and imposed visuospatial constraints via depth changes of the converging defender(s), with the 1DS inferred to pose less visuospatial constraints than the 2DS. Because the direction arrows were two-dimensional, it was assumed that they imposed limited visuospatial constraints. The temporal constraints imposed by the stimuli conditions increased in difficulty in the following order: AP, 1DS, 2DS, and AUNP. The AP condition imposed no temporal constraints, whereas the ranking of the 1DS, 2DS, and AUNP conditions was established from pilot testing on 10 men made up of four high-level (mean ± SD playing experience = 13.5 ± 4.3 yr) and six low-level soccer players (5.0 ± 2.1 yr). The test identified how much time before reaching the force plate the participants needed for the "directional cues" to be presented so they could sidestep successfully without missing the force plate. The timing of the directional cues was selected as the time points when the projected defenders first planted their feet to change directions in the 1DS and 2DS and the appearance of the arrow in the AUNP. The directional cue in the AUNP needed to be presented earliest: 453 ± 37 ms before the participants reached the force plate, followed by the 2DS (361 ± 84 ms) and 1DS (215 ± 34 ms).

Before testing, participants were familiarized with the visual stimuli and cutting maneuvers in a practice session. In this session, the presentation timing of the arrow in the unplanned condition (AUNP) was adjusted for each participant to account for individual reaction times. The minimal time required to complete the AUNP was then used as the time base for presentation of the directional cues in the 1DS and 2DS, providing participants with more than sufficient time to perform cutting while temporally constraining their maneuvers at different levels. Approximately 1 h was required for participants to become fully familiarized with the testing requirements.

In all stimuli conditions, cutting trials were considered successful when participants maintained an approach velocity of 4.5 ± 0.5 $m \cdot s^{-1}$ between two infrared timing gates and achieved a cut angle of 45° ± 10°. If participants did not maintain their approach velocity, the word "abort" appeared on the screen, which required a retrial. Cut angle was ensured by requiring participants to pivot on the force plate and then travel through either two pairs of cones at 45° to the center of the force plate. The initial commitment toward an incorrect direction of travel followed by postural correction and missing foot contact with the force plate was also considered an unsuccessful trial and required a retrial. To avoid force plate targeting, participants were instructed to focus on the screen during the approach run. Further, a marker was positioned at the start of each participant's approach run so that their natural cadence resulted in foot contact of the dominant leg on the force plate.

Data collection. The previously developed Stereoscopic System (28) was used to present the different stimuli conditions. During the cutting tasks, the participant's three-dimensional motion data were synchronously collected at 250 Hz using a 12-camera Vicon MX motion analysis system (ViconPeak Ltd., Oxford, UK). Ground reaction forces were synchronously collected at 2 kHz using a 1.2 × 1.2-m AMTI force plate (Advanced Mechanical Technology Inc., Watertown, MA).

To facilitate a three-dimensional motion analysis, 32 retroreflective markers were affixed to each participant following the UWA lower body and torso marker set and model (4–7,15,16,26). Single markers were attached to the left and right calcanei, left and right head of the first and fifth metatarsals, left and right anterior and posterior superior iliac spines, sternal notch, xiphoid process, seventh cervical vertebrae, twelfth thoracic vertebrae, and the left and right acromion processes. Three-marker clusters were attached to the thighs and shanks of both legs. To define each ankle joint center, single markers were attached to the medial and lateral malleoli in "static" calibration trials, which were removed for the dynamic trials. A six marker pointer was used following the Calibrated Anatomical Systems Technique (9) to identify the positions of the medial and lateral femoral condyles and to locate the knee joint centers (9). This method has been shown to reduce skin movement artifact during the analysis of dynamic movements (9). Functional knee and hip tasks were performed to identify knee joint centers and axes and hip joint centers and axes, respectively (7,11,16). A foot calibration rig was used to establish the foot adduction–abduction and rear foot inversion–eversion in standing (7).

Using the UWA lower body and torso model further reduces errors associated with inappropriate marker placements on anatomical landmarks and artifacts resulting from skin movement. This is due to the knee axes and hip joint centers located using functional methods rather than anatomical landmarks, resulting in more reliable kinematic and kinetic data (7,11). Furthermore, because the intratester reliability is usually higher than intertester reliability, the same experienced researcher attached the markers on every participant during testing sessions.

Joint angles and moments were calculated using our established methods (7,15,16). The three-dimensional motion and ground reaction force data were low-pass filtered at a cutoff frequency of 16 Hz, using a fourth-order, zero-lag, Butterworth recursive filter. The cutoff frequency was determined using residual analysis (40) and visual inspection of the kinematic and kinetic data. Applying the same filter and cutoff frequency to both motion and GRF data lowers the possibility for joint kinetics artifact, following the findings and recommendations of McLean et al. (31–33). The segment and joint angles were determined using the kinematic model described by Besier et al. (7) and were expressed in joint coordinate systems according to the standards of the International Society of Biomechanics. External joint moments were calculated using inverse dynamics (7) with the body segment parameter values from de Leva (13).

The kinematic and kinetic data were analyzed in weight-acceptance (WA) phase during stance. WA was identified using a custom Matlab (The Mathworks, Inc., Natick, MA) program and spanned from initial foot contact to the first trough (4–6,11,15,16) in the unfiltered vertical ground-reaction force. WA was selected for analysis as the peaks of the knee valgus and internal rotation moments occur in this phase (15,16), suggesting a period of high ACL loading (4–6,32,33). Furthermore, video-based studies of ACL injuries suggest that the ligament ruptures in this period (12,24). Trunk and lower body kinematic data were analyzed at initial foot contact as knee valgus moments seem to be influenced by the postures adopted at this time point (16,33). Subsequently, the set of dependent biomechanical variables were created. At initial foot contact, hip flexion–extension, adduction–abduction, and internal–external rotation angles, and frontal plane trunk flexion were extracted for analysis. During WA, mean peak knee valgus and internal rotation moments were extracted. All knee moments were normalized to body weight and height, with positive joint moments being valgus and external rotation. Joint angles were reported as positive in flexion, adduction, and internal rotation, with lateral trunk flexion toward the sidestep direction being positive.

Statistical analysis. The dependent biomechanical variables in WA were averaged across three sidesteps performed in response to the respective stimuli conditions. Stimuli conditions were treated as repeated measures, whereas skill level was treated as an independent factor. Using the Statistical Package for the Social Sciences (Version 16.0; SPSS Inc., Chicago, IL), within- and between-group ensemble mean differences were ascertained using a 4 × 2 (stimuli × skill level) mixed-design ANOVA, with $P < 0.05$. Differences that approached significance were defined as $0.05 < P < 0.08$. Significant main and interaction effects were assessed using *post hoc* tests with Sidak correction. Before analysis, all data were inspected for assumptions of normality, which were fulfilled, satisfying the criteria for the performance of mixed-design ANOVA.

RESULTS

Hip postures were affected by stimuli type and skill levels (Table 1). Hip flexion postures were similar in the AP and 1DS, which were approximately 3° and 7° greater than that in the 2DS ($P < 0.03$ and $P < 0.001$, respectively) and AUNP ($P < 0.001$ for both comparisons), respectively. Hip flexion was also 3.1° greater in the 2DS compared with the AUNP ($P < 0.003$). Hip abduction was smaller in the preplanned (AP) condition compared with all the other reactive stimuli conditions: 1DS, 4.2° higher ($P < 0.02$); 2DS, 3.4° higher ($P < 0.03$); and AUNP, 9° higher ($P < 0.001$). Conversely, hip abduction was larger in the AUNP compared with 1DS (4.8°, $P < 0.001$) and 2DS (5.5°, $P < 0.001$). Hip external rotation postures were similar in 1DS and 2DS, which were 2° to 3° smaller compared with AP ($P < 0.03$ for both comparisons) and AUNP ($P < 0.05$ for both comparisons), respectively.

Regardless of stimuli, high-level players had less hip abduction than low-level players (3.5° less; $P < 0.05$). *Post hoc* analysis showed that the high-level players (−8.8° ± 4.9°) displayed 4.7° less hip abduction in the AP compared with the low-level players (−13.5° ± 6.4°), $P < 0.03$. Hip abduction in the high-level players (−12.7° ± 4.8°) also tended to be 3.9° lower than the low-level players (−16.6° ± 5.9°) in the 2DS, $P < 0.06$, with a medium effect size, $d = 0.70$.

The trunk was more upright in the frontal plane in the AP compared with the reactive stimuli conditions (AUNP, 1DS, and 2DS). The trunk was 2° more upright in the AP compared with the 2DS ($P < 0.02$) and 4° more upright compared with the 1DS ($P < 0.001$) and AUNP ($P < 0.001$). The trunk was also more upright in the 2DS by approximately 2° compared with the AUNP ($P < 0.02$) and exhibited a similar trend with a small effect size when compared with the 1DS ($P < 0.07$, $d = 0.29$). Trunk posture was not affected by skill level.

The peak knee valgus moments were significantly affected by stimuli and approached significance for skill level (Table 2). These moments in the AUNP condition were larger by 69% compared with the AP, 40% compared with the 1DS, and 43% compared with the 2DS ($P < 0.001$ for all comparisons).

Importantly, there was a significant interaction effect on peak knee valgus moments between stimuli and skill level (Table 2). In the high-level group, peak knee valgus moments were smallest in the AP (−0.31 ± 0.28 $N \cdot kg^{-1}$) and 2DS (−0.31 ± 0.22 $N \cdot kg^{-1}$) and increased in the following order: 1DS (−0.43 ± 0.28 $N \cdot kg^{-1} \cdot m^{-1}$) and AUNP (−0.59 ± 0.25 $N \cdot kg^{-1}$). In the low-level group, peak knee valgus moments increased in the following order: AP (−0.47 ± 0.26 $N \cdot kg^{-1}$), 1DS (−0.51 ± 0.29 $N \cdot kg^{-1}$), 2DS (−0.60 ± 0.27 $N \cdot kg^{-1}$), and AUNP (−0.72 ± 0.36 $N \cdot kg^{-1}$). *Post hoc* analysis showed that the high-level players had peak valgus moments that were 48% smaller in the 2DS compared with the low-level group ($P < 0.004$).

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TABLE 1. Mean hip flexion–extension, adduction–abduction, and internal–external rotation, and lateral trunk flexion angles at initial foot contact across different stimuli conditions and player skill levels.

	Hip			Trunk
	Flexion (+ve) (°)	Abduction (−ve) (°)	External Rotation (−ve) (°)	Lateral Flexion Contralateral to Sidestep Direction (−ve) (°)
Stimulus				
AP	47.5 ± 7.3	−11.2 ± 5.9	−6.8 ± 7.5	−6.5 ± 6.0
1DS	48.0 ± 7.6	−15.4 ± 6.2	−4.1 ± 6.8	−10.2 ± 5.6
2DS	44.5 ± 7.0	−14.6 ± 5.6	−4.6 ± 7.9	−8.7 ± 4.6
AUNP	41.4 ± 6.6	−20.2 ± 5.0	−7.2 ± 8.6	−10.3 ± 4.0
Stimulus effect *P* value	<0.001*	<0.001*	<0.001*	<0.001*
Post hoc results	AP > 2DS*	AP > 1DS*	1DS > AP*	AP > 1DS*
	AP > AUNP*	AP > 2DS*	1DS > AUNP*	AP > 2DS*
	1DS > 2DS*	AP > AUNP*	2DS > AP*	AP > AUNP*
	1DS > AUNP*	1DS > AUNP*	2DS > AUNP*	2DS > 1DS**
	2DS > AUNP*	2DS > AUNP*		2DS > AUNP*
Skill level				
High level (HL)	46.8 ± 5.7	−13.6 ± 4.8	−4.5 ± 8.0	−8.8 ± 5.8
Low level (LL)	43.7 ± 4.3	−17.1 ± 6.0	−6.8 ± 7.5	−9.0 ± 4.2
Skill effect *P* value	0.210	0.046*	0.376	0.901
Post hoc results		HL > LL in AP*		
		HL > LL in 2DS**		
Stimulus × skill *P* value	0.732	0.430	0.510	0.127

Data are presented as mean ± SD unless otherwise indicated.
*Significantly different at $P < 0.05$.
**Approaching significantly different at $0.05 < P < 0.08$.

The peak knee internal rotation moments were only affected by the stimuli conditions. These moments significantly decreased in the AUNP by approximately 32% compared with the AP ($P < 0.01$), 1DS ($P = < 0.001$), and 2DS ($P < 0.01$).

DISCUSSION

There have only been a limited number of laboratory-based studies that incorporated game conditions when investigating evasive sidestepping, but these have revealed some biomechanical variables that may be related to the risk of ACL injury (5,10,18,32). Despite video-based research suggesting that defenders can draw the visual attention of athletes and thereby affect ACL injury risk during sidestepping (24,36), it has not been integrated into laboratory-based studies for further confirmation. Furthermore, others have reported that skill level affects the ability of athletes to pick up sport-specific visual cues for movement preparation and execution (1). Therefore, in an attempt to incorporate all these aspects into one study, our first aim was to introduce three-dimensional video projections of defensive opponent(s) (25) to investigate if quasi–game-realistic visual conditions affect sidestepping in a laboratory setting. Our second aim was to investigate the biomechanics of high-level and low-level soccer players sidestepping in response to different quasi–game-realistic visual stimuli. Our first two hypotheses were generally supported, as most postures and resultant knee moments became more "unsafe" from an ACL injury prevention perspective (6,7,15,16,22,24,31,36) when the temporal and visuospatial constraints imposed by the stimuli conditions were higher. Our third hypothesis was also partially supported, as hip abduction angle and knee valgus moments were lower for the high-level players compared with the low-level players although only in the 2DS.

All trunk and lower limb postures at initial foot contact were affected by the stimuli conditions independent of skill level. The hip external rotation in the defender scenarios was lower by similar amounts compared with both arrow conditions. This suggests that changes in hip external rotation were less dependent on the varying levels of temporal constraints imposed by the stimuli conditions but rather on the sport specificity and visuospatial realism of them. This finding is supported by two independent studies, which found no differences in hip rotation compared with preplanned landing and sidestepping, when temporal (8) and visuospatial constraints (32) were imposed via visual stimuli that were not sport specific. Decreased external rotation (hence greater internal rotation) of the hip in the defender scenarios may contribute to higher knee valgus moments (31), which could lead to knee valgus buckling and rupture of the ACL (21).

TABLE 2. Average peak valgus and internal rotation moments at the knee in WA across different stimuli conditions and player skill levels.

	Peak Valgus (+ve) ($N \cdot kg^{-1}$)	Peak Internal Rotation (−ve) ($N \cdot kg^{-1}$)
Stimulus		
AP	0.39 ± 0.27	−0.21 ± 0.10
1DS	0.47 ± 0.28	−0.23 ± 0.10
2DS	0.46 ± 0.28	−0.21 ± 0.10
AUNP	0.66 ± 0.30	−0.15 ± 0.11
Stimulus effect *P* value	0.000*	0.000*
Post hoc results	AP < 1DS*	AP < AUNP*
	AP < AUNP*	1DS < AUNP*
	1DS < AUNP*	2DS < AUNP*
	2DS < AUNP*	
Skill level		
High level (HL)	0.41 ± 0.26	−0.20 ± 0.11
Low level (LL)	0.58 ± 0.29	−0.20 ± 0.09
Skill effect *P* value	0.078**	0.895
Post hoc results	HL < LL in 2DS*	
Stimulus × skill *P* value	0.036*	0.865

Data are presented as mean ± SD unless otherwise indicated.
*Significantly different at $P < 0.05$.
**Approaching significantly different at $0.05 < P < 0.08$.

However, knee valgus moments were largest in the AUNP, which also yielded the largest hip abduction and lateral trunk flexion postures. As such, the contributions of hip abduction and lateral trunk flexion to larger knee valgus moments could outweigh the effects of the increased hip internal rotation observed in the defender scenarios. Dempsey et al. (16) reported that increased lateral trunk flexion and a "foot-wide" technique (increased hip abduction) were sidestepping postures that increased knee valgus moments and ACL injury risk (21).

Hip flexion was smallest in the AUNP and largest in the AP and 1DS, suggesting it increased with decreasing levels of temporal constraint. It has been previously reported that hip flexion decreases during unplanned movement tasks (8), remains constant in planned sidestepping tasks (18), and increases when sidestepping is performed in response to a static defender (32). This further reinforces the hypotheses that less flexed/more extended hip postures are adopted when sidestepping is performed under tight temporal constraints. Decreased initial contact hip flexion during the stance phase of unplanned movements (AUNP) may place the hamstrings at a mechanical disadvantage (14) for supporting large anteriorly directed tibial shear loads and external out of plane loads (28), thereby increasing the risk of ACL injury.

Hip abduction was predominantly influenced by the level of temporal constraints imposed by the stimuli conditions. Hip abduction was largest in the AUNP, moderate in the defender scenarios, and smallest in the AP. There are still equivocal interpretations regarding the effect of increased hip abduction on ACL injury risk (8,18). Increased hip abduction may result in a lateral shift of the center of pressure relative to the knee joint center, thereby increasing knee valgus moments (18). Conversely, increased hip abduction has also been suggested to reduce knee valgus and hence protect the ACL (8). In the current study, the large hip abduction measured in the AUNP coincided with the highest measured knee valgus moments (Table 2). This suggests that increased hip abduction during sidestepping may indirectly increase ACL injury risk predisposition.

Supporting our third hypothesis, the high-level players exhibited smaller hip abduction when sidestepping was performed in the AP and 2DS compared with the low-level players (Table 2). The difference in the AP may reflect greater hip adductor strength and/or upper body control in the high-level group, acting to keep their hips closer to the body's midline during sidestepping for the maintenance of postural stability. In addition, the decreased hip abduction angle in the 2DS may also reflect the enhanced visual–perceptual skills of the high-level players in using the quasi–game-realistic visual cues to engage in earlier control of the pelvis, hip, and sidestepping limb. Reducing hip abduction and hence avoiding the previously cited "foot-wide" technique (16) during sidestepping in the 2DS may be a postural control measure that serves to reduce knee valgus moments in skilled athletes.

Increased levels of lateral trunk flexion coincided with increasing levels of temporal constraints except in the 2DS. The trunk was most upright when sidestepping was performed in the AP and most laterally flexed contralateral to the sidestepping direction in the 1DS and AUNP. Previous work by Patla et al. (37) suggested that people use lateral trunk flexion instead of support foot placement to redirect the center of mass when changing directions under time constraints. The increased lateral trunk flexion observed in the more temporally constrained 1DS and AUNP may reflect a similar strategy used to redirect center of mass toward the intended direction of the sidestep. Why then was the trunk more upright in the 2DS compared with the 1DS? Because of the increased complexity of the 2DS, participants may have kept their trunks more upright and only used lateral flexion to change direction later into WA phase. Future analyses investigating the timing and magnitude of peak lateral trunk flexion during sidestepping will be required to confirm this.

The kinematic results highlight the effect of visual information on sidestepping postural control that is relevant to ACL injury etiology (16,31,36). However, ACL injuries occur when loads applied to the ligament are larger than its capacity to sustain them. Consequently, the presented kinematic data need to be evaluated in association with the resultant knee moments to establish the extent to which the kinematic changes are relevant to knee moments and subsequent ACL injury risk.

Knee moments were significantly affected by the visual stimuli. Increased knee internal rotation moments (5,6,12) and increased knee valgus moments in particular (6,21) are well-established key biomechanical variables associated with increased ACL injury risk during sidestepping. Contrary to our hypothesis and the results of Besier et al. (5), peak knee internal rotation moments were significantly decreased in the AUNP compared with the other stimuli conditions. In that study (5), the approach velocity of the participants was 3 $m \cdot s^{-1}$. The current results may be due to the different stimuli used and the 50% faster approach velocity. Future research should investigate both planned and unplanned sidestepping at varying approach velocities to identify potential changes in the biomechanics. Regardless, the magnitude of the internal rotation moments and the differences between stimuli conditions seem insignificant in light of the knee valgus moment results.

Peak knee valgus moments were significantly higher in the stimuli conditions that imposed greater temporal difficulty. Therefore, sidestepping in the AUNP in this research, or other highly temporally constrained conditions, probably entails the highest ACL injury risk. Notably, changes in many of the trunk and lower body postures in the AUNP were the most extreme, when compared with the other stimuli conditions. Training interventions should attempt to shift these sidestepping postures toward that observed in the AP, where valgus moments were the lowest.

The findings of this research clearly show that sidestepping in response to projected three-dimensional defender(s) results in different postures and knee moments to those resulting from the non–game-realistic arrow stimuli. As such, in addition to the established effectiveness of balance and plyometric training in reducing noncontact ACL injuries (20, 27,35), future interventions could incorporate sidestepping technique training (15) while responding to three-dimensional quasi–game-realistic stimuli. Such an approach may improve both the visual–perceptual and the motor components relevant to sidestepping in response to situations that may arise in team sports, maximizing the potential for on-field transference (23) and hopefully minimizing ACL injury risk.

The high complexity of the 2DS was able to differentiate the high-level from the low-level players in terms of their sidestepping strategy, whereas no other condition had this discrimination ability. In the 2DS, the high-level players sidestepped with a safer visual–perceptual–motor strategy that resulted in smaller hip abduction angles and knee valgus moments compared with the low-level players. During the performance of "open" skills such as evasive sidestepping in perceptually demanding situations, visual–perceptual skill and decision-making abilities are believed to act as the limiting factors to performance rather than movement production (1,2). The current work suggests that this is also reflected in safer sidestepping. The safer sidestepping strategy used by the high-level players may reflect their ability to identify directional cues in the quasi–game-realistic 2DS faster than the low-level players, thereby allowing the high-level players more time and space to perform the maneuver. Future research could track the gaze fixations of high-level players to assist in identifying important visual cues used to create increased time and space during games. If important cuing strategies can be identified, low-level athletes could be trained to focus on these cues in game environments (38). Training may help improve the abilities of these less skilled players to "buy themselves more time and space" in game situations to prepare and execute sidestepping maneuvers more safely. Although this tenet cannot be examined in this study, experience and skill acquisition (22) has been associated with ACL injury risk and thus represents a plausible and novel avenue of intervention.

In conclusion, this study has provided new insights into the relationship between visual information and its effect on sidestepping biomechanics. The introduction of the three-dimensional stereoscopic stimuli presents a new approach in the visual presentation of temporal and visuospatial constraints via stimuli that attempt to mimic the game environment. The three-dimensional stereoscopic stimuli facilitate the investigation of the sidestepping maneuver in a controlled and repeatable fashion within a laboratory environment. Using such an approach, which addresses both the movement and the visual–perceptual complexity associated with evasive sidestepping, has been cited to potentially improve the efficacies of ACL injury prevention models (8). Importantly, the safer sidestepping biomechanics exhibited by the high-level players in the 2DS suggests that these players used a more efficient visual–perceptual–motor strategy. This strategy needs to be clearly identified, and, once understood, it may be possible to train low-level and community athletes to develop this ability and sidestep with less risk of sustaining ACL injuries.

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