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Effects of shear reduction shoes on joint loading, ground reaction force and free moment across different cutting angles

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ABSTRACT

This study examined the effects of shear reduction shoes on braking and propulsion ground reaction forces (GRFs), free moments, and joint moments when cutting towards different directions. Fifteen male university basketball players performed sidestep cutting towards 45°, 90° and 135° directions with maximum-effort in shear reduction and control shoes. Two-way (angle x shoe) ANOVAs with repeated measures were performed to determine the interaction and main effects of cutting angle and shoe for all tested variables. Results showed that cutting angles had significant influence on most of the variables, except for the peak-free moment, peak ankle eversion moment and maximum loading rate of resultant shear GRF. The shear reduction shoes significantly delayed the timing to the first peaks of vertical and resultant shear GRFs compared with the control shoes. During propulsion, the shear reduction shoes generated smaller peak propulsion resultant shear and vertical ground reaction forces. Additionally, the shear reduction shoes did not induce distinct frontal and transverse moments at the ankle and knee joints compared with the control shoes. These results suggest that the application of shear reduction structure could be beneficial to attenuate vertical and shear impact peaks, offering additional insights to reduce shear-related injuries.

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KEYWORDS
Shear reduction; free moment; sidestep cutting manoeuvre

Introduction

Basketball game consists of frequent direction changes such as sidestep cutting with rapid braking and propulsion actions, especially for guards and forwards (Brauner et al., 2012). Basketball players change their movement directions in every 3 s (Matthew & Delextrat, 2009). Change of direction (i.e. cutting) movements accounted for 31% of playing time, of which 20% are regarded as high intensity (McInnes et al., 1995). It is reported that cutting movements produced larger posterior and medial ground reaction forces (GRFs) than other typical basketball movements such as running and jumping (McClay et al., 1994a).

Excessive horizontal GRFs, including anteroposterior and mediolateral GRFs, have been identified as contributing factors of cutting related injuries (McClay et al., 1994a; McKay et al., 2001; Sigward & Powers, 2007; Yu & Garrett, 2007), although they are relatively smaller than the vertical GRF. These forces are referred to shear or frictional forces that are tangential to the applied surface. The posterior and medial GRFs of a cutting has been demonstrated to contribute to the larger anterior tibial force and knee abduction moment, which are hypothesized to increase risks of non-contact ACL tear (Sigward & Powers, 2007; Yu & Garrett, 2007). Furthermore, the excessive posterior and medial GRFs were transmitted to foot plantar surface, resulting in foot discomfort and complaints such as calluses and blisters (Cong et al., 2014; De Luca et al., 2012). Since the horizontal GRF may be the contributing factors for cutting related injuries, shear reduction shoe seems necessary to minimize injury risk potential during strenuous cutting movements in basketball.

Sliding between shoe and ground interface are suggested as an effective method for shear cushioning. Previous studies compared the effects of sliding and non-sliding surfaces on lower limb mechanics and its injury rates in tennis strokes (Nigg et al., 1984; Nigg & Segesser, 1988; Nigg et al., 1988). The results indicated that tennis players experienced smaller frictional forces and reported fewer numbers of injuries by three to five times when planting their legs on the sliding surfaces. Another study demonstrated that medial GRF was lowest when basketball players landing on the surface with the largest horizontal sliding movement trials during v-cut and side-shuffle tasks (Nigg et al., 2009). In a similar vein, shoes with shear reduction or sliding constructions such as multi-layer insole or groove-type outsole have been also shown to reduce the peak shear and delay the time to the first peak anterior-posterior GRF during walking (Chan et al., 2013; Lavery et al., 2005). Considering that cutting movements in basketball usually involve a sharp turn/twist of the body (Havens & Sigward, 2015a; Sigward et al., 2015), it is reasonable to suggest that a shoe construction allowing material/structural deformation in horizontal and rotational directions can

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potentially induce a sole-ground sliding and thereby affect GRFs whilst cutting (Lam et al., 2017).

Sidestep cutting is typically characterized with a direction change during shoe-ground contact, resulting in a rotational force/moment applied on the foot or shoe (Andrews et al., 1977; Cong et al., 2014). This rotational moment is known as the free moment, which is a torque about the vertical axis and resists an external/internal rotation of foot/shoe to contribute an acceleration of the body towards a new direction (David & Potthast, 2019; Holden & Cavanagh, 1991). Since free moment is sensitive to the foot pronation/supination, joint rotation of lower extremity as well as rotational resistance of a shoe (Holden & Cavanagh, 1991; Willwacher et al., 2016), the free moment would help to explain knee overuse injuries (Willwacher et al., 2016) and footwear function (Graf & Stefanyshyn, 2013), while Lam et al. (2017) did not report the free moment in their study. The investigation of free moment can provide additional insights in relation to footwear performance and cutting related injuries.

Athletes in team sports frequently change direction towards different cutting angles (Dos'Santos et al., 2018; Taylor et al., 2017). Larger cutting angles required a higher braking and propulsion GRFs to achieve a new movement direction (Havens & Sigward, 2015a; Schot et al., 1995). Additionally, to achieve a sharper cut, the athletes may generate a larger torso torque, pelvis rotation, and trunk lean towards a new direction (Andrews et al., 1977; Havens & Sigward, 2015a; Sigward et al., 2015). When the foot plants on the ground, these body adaptations would further change the application of horizontal GRF vector, including the magnitude and direction. Lam et al. (2017) reported that while shear reduction shoe did not significantly change the braking GRF during lateral shuffling and 45° cutting, participants wearing shear reduction shoe generated greater propulsion horizontal impulse in 45° cutting than wearing control shoe. However, this study did not report any changes of horizontal GRF vectors, which are related to cutting with sharper angles. The investigation of force vector changes can help to examine how and when the deformation of the sole occurs and the underlying mechanism of energy store and release during cutting movements across different cutting angles.

Hence, the purpose of this study was to examine the effect of shear reduction shoes on the braking and propulsion GRFs, free moments and joint loadings when performing sidestep cutting towards different directions (45°, 90° and 135°). We hypothesized that shear reduction shoes would influence the peaks, impulses and loading rates of GRFs, free moments as well as joint loadings during cutting movements. Additionally, these tested variables might be angle-dependent and their responses might change across different cutting angles.

Methods

Experimental shoe conditions

Two pairs of Li Ning basketball shoes with size of US9.0 [shear reduction shoes and Yushuai IX (Control), Figure 1)] were used in this study. Both shoes had the same material and hardness of the midsole and insole as well as shoe last as specified by the shoe manufacturer. The shear reduction shoe was built with the cut-out design at the forefoot region (Figure 1), as described in the previous study (Lam et al., 2017). The mechanical test data showed that rotational stiffness of shear reduction shoes in both clockwise and counterclockwise directions were smaller than the control shoes, indicating that shear reduction shoe would allow for larger rotational deformation of a midsole. The control shoe was commercially available in the market.

Figure 1. Test shoe conditions. Top: shear reduction shoe and bottom: control shoe.

Participants

Fifteen male university basketball players (age 22.3 ± 1.6 years; height 1.80 ± 0.03 m; mass 72.0 ± 5.6 kg) were recruited in this study. All participants had the foot length of US size 9 with a maximum tolerance of ± 0.5 for heel-to-toe length. Their average experience of basketball competition was 6.5 ± 2.2 years and training time was 9.6 ± 4.7 hours per week. All participants reported right-leg dominance and this was confirmed by asking the participants to kick a ball at a target placed 4 m away as described previously (Van Melick et al., 2017). They had no injuries or abnormalities in the lower extremities in the past 6 months. All participants were clearly informed with the possible risks of the movement tasks and gave their written consents before the experiments. The experimental protocol was approved by the faculty ethics committee.

Apparatus and tasks

All the 45°, 90° and 135° sidestep cutting conditions (Figure 2) were anticipated and administered in the biomechanical laboratory. These are the typical cutting angles performed in basketball games (McClay et al., 1994b; Nigg et al., 2009; Schreurs et al., 2017; Xie et al., 2012). A 1.2 m x 1.2 m force platform (Advanced Mechanical Technology Inc, Watertown, USA, sampling at 1000 Hz) and its surrounding were covered with the standard basketball indoor wooden surface to measure the GRFs during cutting tasks. The marker trajectories were measured using an eight-camera motion analysis system (Vicon, Oxford Metrics, UK, sampling at 200 Hz). For each sidestep cutting condition, participants initiated forward running

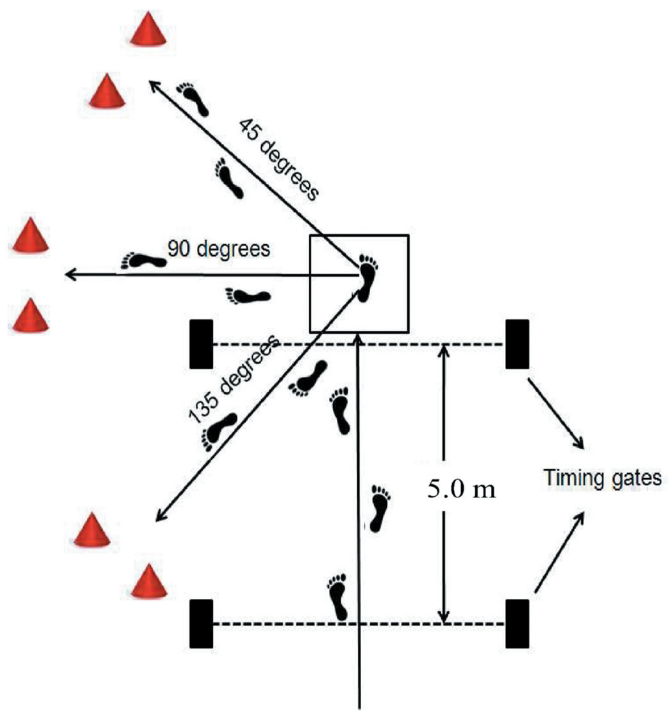

Figure 2. Sidestep cutting tasks.

from 5.0 m away from the force platform. The approach speed of 5.0 ± 0.25 m/s was controlled with the timing gates (Smartspeed, Fusion Sport Inc., Burbank, CA, USA), which is commonly used in previous cutting studies (Lam et al., 2015). Then, participants stepped onto the force platform with their dominant feet and performed the running towards the left directions (45°, 90° and 135° cutting angles, Figure 2) with the maximum effort to pass through the target pylons. The pylons were positioned at 1.5 m from the centre of the force platform. All timing gates (Start and End) were set at a height of 1.06 m and a separated width of 3 m (Lam et al., 2015).

Procedure

Reflective markers were attached over the greater trochanter, medial and lateral malleolus, medial and lateral epicondyles, the first, second and fifth metatarsal heads, and the posterior midpoint of the heel counter. Three triad markers were attached over the shoe heel counter, tibia and thigh to record movement trajectories of the shoe, shank and thigh segments, respectively (Collins et al., 2009; Lam et al., 2015). Prior to the data acquisition, participants were instructed to perform a 15-minute warm up, including self-selected stretching and jogging as well as familiarization with the sidestep cutting conditions. For each shoe condition, participants performed the sidestep cutting in respective 45°, 90° and 135° in a randomized order. Only successful trial was considered when the approach speed within 5% of the target speed and the ground contact time was within 2.5% of the averaged contact time of cutting task (Havens & Sigward, 2015a, 2015b). The foot position of the right-leg cutting step was also committed. To minimize physical fatigue, three successful trials were collected for each of the movement and shoe conditions (Cloak et al., 2010; Kimura & Sakurai, 2013; Lam, Qu et al., 2018). Participants were provided 1-min and 10-min resting periods between trials and between shoe conditions, respectively (Girard et al., 2011; Lam et al., 2015; Schreurs et al., 2017).

Data analysis

GRF parameters including the maximum loading rate, timing of the first peak resultant shear and vertical GRFs, peak-free moment during the whole stance phase, peak resultant shear force, peak vertical force, resultant shear impulse and vertical impulse in both braking and propulsion phases were analysed in this study (Figure 3), as these are of direct relevance to sidestep cutting (Chan et al., 2013; David & Potthast, 2019; McClay et al., 1994a; Nigg et al., 2009). The braking phase was defined as the weight acceptance phase with the knee power absorption period during side-cutting movement. The braking and propulsion phases were determined by the maximum knee flexion of the cutting leg (Havens & Sigward, 2015a; Lam et al., 2015; Xie et al., 2012). The stance phase of each sidestep cutting condition was identified as the period from initial contact of the foot to take-off determined when the vertical GRF first exceeded and went below 10 N (Lam et al., 2017). To compare GRF variables across tested conditions, GRF data were filtered with a cut-off frequency of 100 Hz and then normalized with body mass (Kristianslund et al., 2012; Nigg et al., 2009).

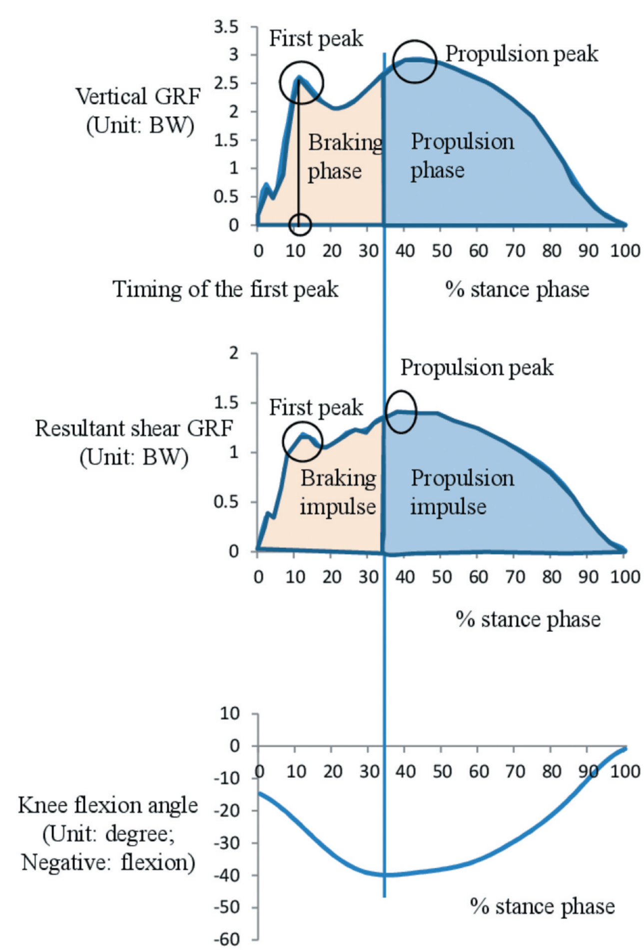

Figure 3. Definitions of GRF related variables.

The anteroposterior GRF obtained from the force platform was re-aligned with respect to the longitudinal axis of the foot/shoe using the shoe progression angle based on the toe and heel markers (Cong et al., 2014). The re-aligned GRF represented the force vector applied on the shoe sole relative to the direction of shoe progression during cutting movements.

The loading rate is described as the force slope from initial contact to the first peak force/impact peak and it is often investigated to evaluate the shoe cushioning and potential risk factors for overuse running injuries (Lam, Liebenberg et al., 2018; Milner et al., 2006). The larger loading rate is referred to a shorter time reaching to the first peak force (Chan et al., 2013; Lam, Liebenberg et al., 2018). Maximum loading rate was defined as the maximum value reached by the force slopes during every 1% of the stance period from initial contact to initial peak force (Cong et al., 2014).

To calculate external ankle and knee moments in three orthogonal planes, both raw GRF and movement data were filtered using a fourth-order low-pass Butterworth filter with the same cut-off frequency of 15 Hz (Kristianslund et al., 2012). External knee valgus and flexion moments abducted and flexed the knee, while external knee moment in transverse plane rotated the knee (Kimura & Sakurai, 2013). The joint moments were normalized with the body weight (BW) for further analyses.

Statistical analysis

Three trials of each variable were firstly averaged for each participant and then calculated for subsequent statistical analyses. The Shapiro-Wilk test was used to investigate the normality of the dataset. Most of the tested variables were normally distributed except for the peak knee valgus moment for control shoes and maximum loading rate of resultant shear force for shear reduction shoes in 45° sidestep cutting, peak-free moment for shear reduction shoes in 90° sidestep cutting, peak propulsion resultant shear forces for both shoes as well as peak propulsion vertical force and propulsion resultant shear impulse for the control shoes in 135° sidestep cutting. Additionally, the timing of the first peaks for both resultant shear and vertical GRFs were not normally distributed for shear reduction shoes in 135° and control shoes in 90° sidestep cutting. Inter-trial reliability of all dependent variables was assessed with intra-class correlation coefficient [ICC (3, 1)]. Reliability was classified as slight (0.00–0.20), fair (0.21–0.40), moderate (0.41–0.60), substantial (0.61–0.80), and almost perfect (>0.80) according to Altman's classification (Altman, 1991).

Two-way-repeated measure ANOVA (cutting angle x shoe) were used to determine the interaction and main effects of cutting angles (45°, 90° and 135°) and shoes (shear reductions and control shoes) for all dependent variables. Greenhouse-Geisser adjustments were used if the sphericity was violated. Post-hoc Bonferroni comparison was then performed to identify significant differences between cutting angles. When significant interaction between shoe and cutting angle was determined, further simple main effect was used to identify significant differences between shoes and between cutting angles. Significance was set at 0.05. Effect size was calculated as partial eta-squared (η_p^2) for ANOVA. The effect size was classified as trivial ($\eta_p^2 < 0.01$), small ($0.01 \leq \eta_p^2 < 0.06$), medium ($0.06 \leq \eta_p^2 < 0.14$) and large ($\eta_p^2 \geq 0.14$) (Cohen, 1998). All statistical analyses were performed using SPSS 21.0 (IBM Corp., Armonk, NY, USA).

Results

ICC

The ICCs among trials were higher than 0.60 for most of the variables (Table 1), representing a substantial or perfect reliability according to Altman's classification (Altman, 1991). Moderate reliability (ranged from 0.44 to 0.60) was found for the propulsion resultant shear and vertical force impulses, maximum loading rates and the timing of the first peaks of the resultant shear and vertical GRFs, peak free moment, and peak ankle eversion moment.

Braking phase

There was no significant interaction between shoe and cutting angle ($P > 0.05$) for GRF variables in braking phase. The shear reduction shoes were found to significantly delay the occurrence of the first peak resultant shear ($P = 0.011$) and vertical ($P = 0.012$) GRFs compared with the control shoes. However, no significant shoe effects were determined on the peak force magnitudes, impulses and maximum loading rates of both resultant shear and vertical forces in the braking phase ($P > 0.05$, Table 2).

Cutting angle had significant influences on most of the GRF variables except for the maximum loading rate of the resultant shear GRF. Cutting to 135° generated a larger peak braking resultant shear GRF [F (1.350, 18.907) = 8.290, $P = 0.006$] but a smaller peak braking vertical GRF [F (2, 28) = 10.563, $P < 0.01$] than cutting towards 45°. As the cutting angle increased, the

Table 1. Intra-class correlation coefficient (ICC) between trials of all dependent variables.

Variables	ICC (*class*)
Contact time (s)	0.93 (*almost perfect*)
Peak braking resultant shear force (BW)	0.70 (*substantial*)
Peak braking vertical force (BW)	0.75 (*substantial*)
Braking resultant shear impulse (BWs)	0.95 (*almost perfect*)
Braking vertical impulse (BWs)	0.65 (*substantial*)
Peak propulsion resultant shear force (BW)	0.64 (*substantial*)
Peak propulsion vertical force (BW)	0.88 (*almost perfect*)
Propulsion resultant shear impulse (BWs)	0.55 (*moderate*)
Propulsion vertical force impulse (BWs)	0.47 (*moderate*)
Timing of the first peak resultant shear force (% stance phase)	0.60 (*moderate*)
Timing of the first peak vertical force (% stance phase)	0.58 (*moderate*)
Timing of the first peak vertical force (% stance phase)	0.44 (*moderate*)
Maximum loading rate of vertical force (BW/ms)	0.50 (*moderate*)
Peak free moment (Nm/kg)	0.55 (*moderate*)
Peak ankle dorsiflexion moment	0.78 (*substantial*)
Peak ankle eversion moment	0.60 (*moderate*)
Peak ankle external moment	0.72 (*substantial*)
Peak knee flexion moment	0.65 (*substantial*)
Peak knee valgus moment	0.82 (*almost perfect*)
Peak knee internal moment	0.90 (*almost perfect*)

Table 2. GRF variables [mean (SD) and ANOVA results] during braking and propulsion phases in 45°, 90°, and 135° sidestep cutting.

Variables	Shoes	Cutting angles			ANOVA results					
					Interaction		Shoe effects		Angle effects	
		45°	90°	135°	P	η_p^2	P	η_p^2	P	η_p^2
Contact time (s)	Shear	0.19 (0.02)	0.28 (0.05)	0.40 (0.05)	0.371	0.062 (M)	0.220	0.105	**< 0.01**	0.878
	Control	0.19 (0.03)	0.26 (0.06)	0.39 (0.07)				(M)	***#&**	(L)
Peak braking resultant shear force (BW)	Shear	1.63 (0.39)	1.78 (0.36)	1.87 (0.37)	0.053	0.189	0.342	0.065	**0.006**	0.372
	Control	1.58 (0.37)	1.91 (0.32)	1.96 (0.36)		(L)		(M)	**&**	(L)
Peak braking vertical force (BW)	Shear	2.81 (0.60)	2.42 (0.54)	2.25 (0.36)	0.186	0.113 (L)	0.883	0.002	**< 0.01**	0.430
	Control	2.69 (0.61)	2.49 (0.39)	2.28 (0.39)				(T)	**&**	(L)
Braking resultant shear impulse (BWs)	Shear	0.19 (0.03)	0.29 (0.04)	0.39 (0.04)	0.917	0.006	0.559	0.025	**< 0.01**	0.947
	Control	0.19 (0.03)	0.30 (0.04)	0.40 (0.04)		(T)		(S)	***#&**	(L)
Braking vertical impulse (BWs)	Shear	0.15 (0.05)	0.19 (0.05)	0.25 (0.04)	0.597	0.036	0.778	0.006	**< 0.01**	0.776
	Control	0.14 (0.05)	0.19 (0.04)	0.25 (0.05)		(S)		(T)	***#&**	(L)
Peak propulsion resultant shear force (BW)	Shear	1.45 (0.19)	1.46 (0.31)	1.2 (0.24)	0.105	0.149	**0.024**	0.315	**< 0.01**	0.471
	Control	1.46 (0.24)	1.62(0.32)	1.29 (0.31)		(L)		(L)	**#&**	(L)
Peak propulsion vertical force (BW)	Shear	2.58 (0.27)	1.99 (0.32)	1.53 (0.21)	0.308	0.081	**0.028**	0.300	**< 0.01**	0.862
	Control	2.63 (0.32)	2.16 (0.33)	1.63 (0.28)		(M)		(L)	***#&**	(L)
Propulsion resultant shear impulse (BWs)	Shear	0.10 (0.02)	0.15 (0.03)	0.19 (0.03)	0.140	0.131	0.638	0.016	**< 0.01**	0.834
	Control	0.12 (0.02)	0.15 (0.02)	0.19 (0.03)		(M)		(S)	***#&**	(L)
Propulsion vertical force impulse (BWs)	Shear	0.18 (0.03)[a]	0.21 (0.03)[b]	0.24 (0.03)[bc]	**0.007**	0.300	0.406	0.050	**< 0.01**	0.562
	Control	0.20 (0.03)	0.20 (0.03)	0.25 (0.04) [bc]		(L)		(S)		
Timing of the first peak resultant shear force (% stance phase)	Shear	18.78 (10.15)	18.79 (5.78)	13.14 (4.81)	0.828	0.006	**0.011**	0.379	**0.002**	0.395
	Control	12.88 (5.96)	14.04 (8.68)	8.04 (3.72)		(T)		(L)	**#&**	(L)
Timing of the first peak vertical force (% stance phase)	Shear	21.04 (10.75)	17.64 (6.06)	13.04 (5.21)	0.883	0.003	**0.012**	0.374	**0.001**	0.396
	Control	16.42 (6.85)	13.68 (7.46)	9.18 (4.20)		(T)		(L)	**&**	(L)
Max loading rate of resultant shear force (BW/ms)	Shear	0.11 (0.05)	0.08 (0.03)	0.09 (0.03)	0.141	0.130	0.291	0.079	0.174	0.117
	Control	0.10 (0.05)	0.10 (0.04)	0.11 (0.02)		(M)		(M)		(L)
Max loading rate of vertical force (BW/ms)	Shear	0.17 (0.07)	0.13 (0.06)	0.11 (0.04)	0.134	0.144	0.295	0.078	**0.002**	0.369
	Control	0.16 (0.04)	0.14 (0.05)	0.13 (0.03)		(L)		(M)	**&**	(L)
Free moment (Nm/kg) – counter-clockwise direction of right shoe	Shear	21.20 (6.48)	20.51 (5.08)	17.64 (3.98)	0.074	0.170	0.266	0.087	0.596	0.036
						(L)		(M)		(S)
	Control	19.75 (5.55)	21.60 (7.18)	20.99 (6.47)						

Effect size: trivial (T), small (S), medium (M), large (L).
* = significant difference between 45° and 90°; # = significant difference between 90° and 135°; & = significant difference between 45° and 135°.
When significant interaction effect was found, simple main effect was applied to identify the significant differences between shoes and between cutting angles:
[a]Significant difference from control shoes.
[b]Significant difference from 45°.
[c]Significant difference from 90°.

Table 3. Peak ankle and knee joint moments [mean (SD) and ANOVA results] in 45°, 90°, and 135° sidestep cutting (Unit: Nm/kg).

Variables	Shoes	Cutting angles			ANOVA results					
					Interaction		Shoe effects		Angle effects	
		45°	90°	135°	P	η_p^2	P	η_p^2	P	η_p^2
Peak ankle dorsiflexion moment	Shear	3.17 (0.53)	2.49 (0.48)	2.19 (0.39)	0.250	0.094	**0.033**	0.286	**<0.01**	0.802
	Control	3.29 (0.36)	2.69 (0.43)	2.43 (0.38)		(M)		(L)	***#&**	(L)
Peak ankle eversion moment	Shear	1.97 (0.38)	1.87 (0.36)	1.97 (0.39)	0.101	0.151	0.825	0.004	0.805	0.015
	Control	1.87 (0.25)	1.97 (0.33)	1.94 (0.34)		(L)		(T)		(S)
Peak ankle external moment	Shear	0.78 (0.20)	0.96 (0.16)	1.08 (0.20)	0.199	0.109	0.852	0.003	**<0.01**	0.801
	Control	0.71 (0.19)	1.00 (0.20)	1.09 (0.19)		(M)		(T)	***#&**	(L)
Peak knee flexion moment	Shear	3.95 (0.48)	3.94 (0.49)	3.52 (0.72)	0.505	0.048	**0.045**	0.257	**0.003**	0.336
	Control	4.10 (0.67)	4.30 (0.59)	3.77 (0.68)		(S)		(L)		(L)
Peak knee valgus moment	Shear	1.93 (0.59)	2.84 (0.80)	3.22 (0.83)	0.149	0.127	0.386	0.054	**<0.01**	0.667
	Control	1.91 (0.59)	2.82 (0.87)	3.47 (0.84)		(L)		(S)	***#&**	(L)
Peak knee internal moment	Shear	1.08 (0.25)	1.27 (0.21)	1.35 (0.22)	0.399	0.064	0.512	0.031	**<0.01**	0.648
						(M)		(S)	***&**	(L)
	Control	1.00 (0.17)	1.28 (0.20)	1.33 (0.15)						

Effect size: trivial (T), small (S), medium (M), large (L).
* = significant difference between 45° and 90°; # = significant difference between 90° and 135°; & = significant difference between 45° and 135°.

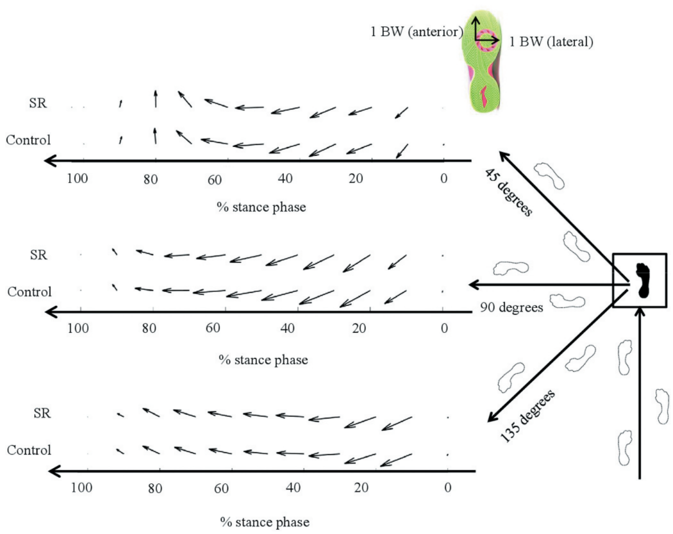

Figure 4. Average resultant shear force vector profiles of fifteen players for 45° (top), 90° (middle), and 135° sidestep cutting (bottom). The direction and magnitude of the arrows are in scales with the actual orientation and amount of the resultant shear force.

braking force impulses of both resultant shear [F (2, 28) = 249.859, P < 0.01, η_p^2 = 0.947 (large)] and vertical [F (2, 28) = 48.561, P < 0.01, η_p^2 = 0.776 (large)] GRFs increased significantly. Compared to 45° sidestep cutting, the occurrences of the first peak resultant shear (P = 0.006) and vertical (P = 0.001) GRFs appeared earlier in 135° sidestep cutting.

Propulsion phase

Significant interaction was observed for propulsion vertical force impulse [F (2, 28) = 5.995, P= 0.007, η_p^2 = 0.300 (large)]. Compared with the control shoes, shear reduction shoes generated significantly smaller propulsion vertical force impulse (P = 0.003) in 45° sidestep cutting. Shoe effects on peak propulsion resultant shear [P = 0.024, η_p^2 = 0.315 (large)] and vertical GRFs [P = 0.028, η_p^2 = 0.300 (large)] demonstrated that shear reduction shoes significantly reduced their magnitudes than the control shoes.

As cutting angle increased, the peak propulsion vertical force significantly decreased [F (2, 28) = 87.196, P< 0.01, η_p^2 = 0.862 (large)], while the propulsion resultant shear impulse significantly increased [F (2, 28) = 70.191, P< 0.01, η_p^2 = 0.834 (large)].

Contact time and free moment

For the contact time, shoe effects were not observed (P> 0.05), while the sharper cutting angle significantly increased the duration of contact time [F (2, 28) = 100.649, P< 0.01, η_p^2 = 0.878 (large)]. The free moments were not different across the shoes and the angles (P> 0.05).

Joint moments

No interactions were determined for all ankle and knee moment variables (P> 0.05, Table 3). Compared with the control shoes, the shear reduction shoes significantly reduced the external ankle dorsiflexion [F (1, 14) = 5.595, P= 0.033, η_p^2 = 0.286 (large)] and knee flexion moments [F (1, 14) = 4.844, P= 0.045, η_p^2 = 0.257 (large)]. The peak knee valgus [F (1.141, 19.792) = 28.089, P< 0.01, η_p^2 = 0.667 (large)] and ankle rotational moments [F (2, 28) = 559.756, P< 0.01, η_p^2 = 0.801 (large)] significantly increased with larger cutting angles, but the shoe effects were not found for these joint moment variables.

Horizontal GRF vectors

The Figure 4 shows the average resultant shear force profiles across time for 45°, 90°, and 135° sidestep cutting. The direction and magnitude of the arrows represented the actual orientation and magnitude of the resultant shear GRF vector, respectively. The directions of resultant shear GRF vectors for all cutting tasks changed in a clockwise pattern from the beginning to the end of the stance phase, while the force vector changed earlier for 135° compared with 45° and 90° sidestep cutting.

Discussions

Applying sliding interfaces has been suggested as an effective mean for shear cushioning. Considering that turning and rotational movements in a cut, shoe constructions allowing material deformation in horizontal/rotational direction could alter cushioning functions. This study extended the work of Lam et al. (2017) on potential application of shear reduction footwear by including additional variables related to cutting and turning movements such as the free moments, and joint moments in transverse plane with three cutting directions (45°, 90°, and 135°).

In contrast to our hypothesis, the shear reduction shoes did not reduce the peak magnitudes and impulse of resultant shear and vertical GRFs during braking phase, compared with the control shoes. However, the shear reduction shoes were found to significantly delay the time to the first peaks of resultant shear and vertical GRFs. Similar results were found in the previous study (Chan et al., 2013), which also showed that straight groove-type shear cushioning delayed the time to the first peak anteroposterior GRF during walking. The shorter time to the peak impact indicates a larger loading rate, which is shown to be related to higher injury risks in sports (Chan et al., 2013; Lam, Liebenberg et al., 2018; Milner et al., 2006).

During the propulsion phase, the current results showed that the shear reduction shoes significantly reduced the peak propulsion resultant shear and vertical GRFs, but did not have any significant effect on resultant shear propulsion impulse compared with the control shoes. This is in line with the previous findings, which showed that higher GRF peak may not necessarily generate a larger impulse or shorter stance time for increased sport performances (Wannop et al., 2010). On the contrary, the large GRF peak may increase peak resultant joint moments, suggesting higher risk of overuse injury. In this study, the shear reduction shoes did not change the propulsion resultant shear impulse and contact time, indicating that the shear reduction shoes might not change sidestep cutting performances.

The knee valgus and internal moments are the key risk factors for ACL rupture (Shin et al., 2011). In the present study, no significant shoe differences were evident for knee valgus and internal rotational moments. This is contrary to the previous cutting study (Nigg et al., 2009), which showed that athletes playing on translational sliding surfaces would reduce ankle joint but increase knee joint moments compared with playing on non-sliding surfaces. The shear reduction shoes with rotational shear reduction structures might have a different working mechanism that proposed from the sliding surfaces study in Nigg et al. (2009) and therefore could not increase the risk for knee injuries.

As expected, cutting towards sharper angles might have induced higher loading intensities. During braking phase, peak braking shear forces and impulses were significantly greater to decelerate the body towards sharper cut direction. In contrast, the peak vertical GRFs reduced, which supported the contention that the direction requirements of GRF are different when cutting across different angles (Dos'Santos et al., 2018). The shear forces, instead of vertical forces, could be more influential for cutting with sharper angles. The contact time was also found to be increased across the cutting angles, although we had controlled the same approach speed in each of the cutting conditions. The longer contact time could be attributed to larger braking resultant shear and vertical impulses when cutting to larger angles, which were required participants to decelerate the body velocity and redirect into a new direction (Havens & Sigward, 2015a, 2015b; Nigg et al., 2009). The current results reveal that cutting towards a sharper angle generated a larger joint loading, especially for knee joint. Increased both knee valgus and internal rotation moments have been suggested to increase ACL strain more than either valgus or internal rotation moment alone (Shin et al., 2011). The free moment did not change as we expected across cutting angles, although the internal knee moment and external ankle moments were larger for 90° and 135° than 45° sidestep cutting. This might be caused by a different cutting strategy by rotating the whole body to achieve the greater direction change, when the athletes cutting to a sharper angle (Dos'Santos et al., 2018). In present study, this pre-orientation was also found for 135° cutting, presented by an earlier direction change in a clockwise pattern of the resultant shear GRFs for 135° compared with 45° and 90° sidestep cutting (Figure 4). Ohkawa et al. (2017) found that the larger relative rotational movement between pelvis and foot had a significant negative correlation with the peak-free moment. Therefore, studying only the foot and knee segmental mechanics might not be sufficient to explain the changes of free moment (Ohkawa et al., 2017). In the future, the combined effects of these related factors including foot pronation (Holden & Cavanagh, 1991) as well as motion patterns of hip, pelvis and trunk (Ohkawa et al., 2017; Willwacher et al., 2016) have to be considered before a viable conclusion can be made.

There were a few limitations in this study when interpreting our results. First, only the cutting (planting) step was investigated in this study. The one or two steps prior to the planting step would provide important insights into the pre-planned movement strategy in deceleration and initiating effective direction changes (Mornieux et al., 2014; Staynor et al., 2020) and might influence the performance of shear reduction shoes during cutting step. Second, the external ground reaction force might not reflect the actual mechanism loading between foot and shoe interfaces. Future investigation should examine the effect of shear reduction shoes on in-shoe shear loading to provide additional insights of underlying mechanism to prevent soft tissues problem (Cong et al., 2014). Third, the effect of shear reduction shoes was evaluated by discrete variables only, which might not identify the changes across the whole stance phase. A curve analysis approaches, such as statistical parametrical mapping (SPM), can be applied in the future. Fourth, while damaged/heavy worn shoes may increase vertical GRF impulse in cutting and landing (Lam et al., 2019; Orloff & Fujino, 2007), future studies may consider providing more pairs of shoes, instead of only one pair of shoes worn by all participants.

Conclusion

Most GRF and joint moment variables were angle-dependent, except for the peak-free moment, peak ankle eversion moment and maximum loading rate of resultant shear GRF. During the braking phase, the shear reduction shoes can provide cushioning by delaying the time to peak resultant shear and vertical GRFs, instead of reducing the peak magnitudes and impulses of GRFs. During the propulsion phase, the shear reduction shoes reduced both peak resultant shear and vertical GRFs. These findings suggest that the rotational shear cushioning has a good potential to attenuate the GRFs and thereby prevent the overuse injuries. However, no significant shoe differences were found for the propulsion resultant shear impulse and contact time, suggesting that the shear reduction shoes might have no influence on the cutting performances.

Disclosure statement

No potential conflict of interest was reported by the authors.

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