

Effects of foot rotation positions on knee valgus during single-leg drop landing: Implications for ACL injury risk reduction



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ABSTRACT

Background: Non-contact anterior cruciate ligament (ACL) injuries commonly occur when athletes land in high risk positions such as knee valgus. The position of the foot at landing may influence the transmission of forces from the ankle to the knee. Using an experimental approach to manipulate foot rotation positions, this study aimed to provide new insights on how knee valgus during single-leg landing may be influenced by foot positions.

Methods: Eleven male recreational basketball players performed single-leg drop landings from a 30-cm high platform in three foot rotation positions (toe-in, toe-forward and toe-out) at initial contact. A motion capture system and a force plate were used to measure lower extremity kinematics and kinetics. Knee valgus angles at initial contact (KVA) and maximum knee valgus moments (KVM), which were known risk factors associated with ACL injury, were measured. A one-way repeated measures Analysis of Variance was conducted ($\alpha = 0.05$) to compare among the three foot positions.

Results: Foot rotation positions were found to have a significant effect on KVA ($p < 0.001$, $\eta^2 = 0.66$) but the difference between conditions (about 1°) was small and not clinically meaningful. There was a significant effect of foot position on KVM ($p < 0.001$, $\eta^2 = 0.55$), with increased moment observed in the toe-out position as compared to toe-forward ($p = 0.012$) or toe-in positions ($p = 0.002$).

Conclusions: When landing with one leg, athletes should avoid extreme toe-out foot rotation positions to minimise undesirable knee valgus loading associated with non-contact ACL injury risks.

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1. Introduction

Anterior cruciate ligament (ACL) injuries commonly occur during sports such as basketball, soccer, and Australian Football [1,2]. These injuries may result in long absence from play [3] and thus negatively impact the careers of athletes. ACL injuries often happen in manoeuvres such as sidestepping and single-leg landing during non-contact situations [4], in which players are not hit by an object or another player [1]. Instead, from the video analyses of ACL injuries, athletes frequently land in high risk positions such as knee valgus positions [5–7] whereby one or both knees are seen moving towards the midline of the body [8]. In the prospective cohort study of female athletes by Hewett et al. [9], athletes who sustained ACL injuries landed at

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higher knee valgus angles (KVA) at initial contact during a drop vertical jump, as compared to the uninjured athletes. In addition, their study showed that knee valgus moments (KVM) predicted ACL injuries with 73% specificity and 78% sensitivity [9]. Among badminton players, higher KVA and KVM were also associated with higher ACL injury risks [10]. Based on a stochastic biomechanical model, Lin et al. [11] similarly considered high KVM as a risk factor of non-contact ACL injury. Using the magnetic resonance imaging scan, Speer et al. [12] further supported valgus as one of the mechanisms of ACL injuries. Collectively, these studies suggest that higher KVA at initial contact and greater KVM could increase the risks of ACL injury. To reduce these risks, knee valgus positions should therefore be avoided when landing from a jump.

Although ACL injury prevention has been studied extensively, there is still a rising trend of the occurrence of ACL injuries [4]. Most studies on ACL injuries examined the knee [9,13], hip [14,15], or trunk [16,17]. Since the foot and ankle form the initial parts of the lower extremity kinetic chain during landing, the position of the foot may influence the transmission of forces from the ankle to the knee [18]. Thus, studying ACL injuries from the foot perspective may provide new knowledge on preventive strategies for non-contact ACL injuries.

In the literature, very few studies have considered the role of the foot in influencing ACL injuries [19–24]. Ishida et al. [21] studied the effect of foot rotation positions on knee rotation during knee valgus. Their protocol which requested participants to move from a standing position to a knee valgus position, however, might not sufficiently simulate the loading during dynamic landing [21]. Cortes et al. [19] studied the effects of sagittal foot-landing positions (fore-foot, rear-foot and preferred) on lower extremity kinematics during double-leg landing and found that knee flexion angle was significantly lower at initial contact for fore-foot landing. Tran and colleagues [23] found differences in hip and knee biomechanics during double-leg landing in toe-in and toe-out positions in comparison to a neutral reference. Since unilateral and bilateral landings are characterised by different knee kinematics and muscle activation levels [25], the results reported by previous studies [19,22–24] on double-leg landing may not be applicable for single-leg landings whereby more non-contact ACL injuries occur [4]. One study on single-leg landing found that maximum knee valgus moment was correlated with toe-out foot position [20]. This study, however, did not compare different foot rotation positions such as toe-forward and toe-in positions, or examine the ACL risk factors at the initial contact of landing whereby ACL strain was the highest [26]. Thus, it will be useful to further examine the influence of foot rotation positions on ACL risk factors both at initial contact and during landing.

The purpose of this study was therefore to investigate the effects of foot rotation positions (toe-in, toe-forward, toe-out) on knee valgus, during single-leg drop-landing. Based on the correlation results reported by Dempsey et al. [20], it was hypothesized that the toe-out position would be characterised by greater knee valgus angles (KVA) at initial contact and higher maximum knee valgus moments (KVM) during landing. These would translate into increased risks of non-contact ACL injury.

2. Methods

2.1. Participants

A power analysis was performed using G*Power (v3.1.9.2, Heinrich-Heine University, Düsseldorf, Germany) based on the results (large effect size in the correlation between external foot rotation and maximum KVM) reported by Dempsey et al. [20]. Using a large effect size of 0.40 for a one-way repeated measures Analysis of Variance [27], a sample size of 12 was required ($\beta = .80$, $\alpha = .05$). Fifteen participants were initially recruited but data of four participants had to be discarded: one dropped out halfway of the study; the other three had incomplete data as markers were not adhering well due to their intense perspiration. Thus, data of the remaining 11 male recreational basketball players (age: mean 23.6 (standard deviation (SD) 1.6) years old; height: mean 1.73 (SD 0.07) m; body mass: mean 66.6 (SD 8.6) kg) were used in this study. Participants had no prior ACL injuries or lower extremity injuries in the last six months, and played basketball at least once a week for a minimum of two years prior to the study. The study was approved by the Institutional Review Board of the university. All participants signed a written consent form before the study began.

2.2. Equipment

The same model of basketball shoes (Nike Zoom Attero, Nike, Inc., Beaverton, OR, USA) was provided to all participants to eliminate the influence of footwear. Retroreflective markers were attached to key body landmarks of the dominant leg using tape (Leukoplast®, BSN medical GmbH, Hamburg, Germany). The dominant leg was self-reported by the participants as the leg that kicked the ball the hardest. The landmarks included sacrum, anterior superior iliac spine, greater trochanter of femur, mid-thigh, medial and lateral knee epicondyles, tibial tuberosity, head of fibular, anterior aspect of shin, medial and lateral malleoli, bottom of the calcaneus (CA1), Achilles tendon insertion point to calcaneus (CAL2), head and base of first metatarsal, head and base of fifth metatarsal and toe (between second and third metatarsal heads). Markers were also attached to the anterior superior iliac spine and greater trochanter of the non-dominant leg for the estimation of the hip joint location. Three-dimensional motion data were captured at 200 Hz using eight digital cameras and the Cortex software (version 1.1.4.368, Motion Analysis Corp, Santa Rosa, CA, USA). Ground reaction forces (GRF) were recorded using a force plate (Kistler type 9287CA, Winterthur, Switzerland) at a sampling rate of 1000 Hz in synchronization with the cameras. Kinematic and kinetic data were further processed using Visual3D (v5.00.33, C-Motion, Germantown, PA, USA).

2.3. Test protocol

This study investigated the biomechanics of single-leg drop-landing by experimentally manipulating foot rotation positions. Participants were asked to carry out a warm-up exercise for five minutes and were given time to practise the drop-landing manoeuvres before data collection commenced. Participants were requested to stand with their dominant leg on a 30 cm-high platform, and drop land onto a force plate using the same leg. Drop-landings were performed in three foot rotation positions presented in a randomized manner: toe-forward, toe-in and toe-out (Figure 1). Participants were requested to face a board, marked with a red cross and hung on a wall at their eye-level, while landing. Upon landing on the force platform with the dominant leg, participants were required to maintain the position for two seconds. A trial was considered successful when the participants dropped off from the raised platform without jumping up, and landed with the entire foot on the force plate, and maintained balance for at least two seconds. Three successful trials of each condition were collected.

2.4. Kinematic and kinetic analyses

Visual3D (v5.00.33, C-Motion, Inc., Germantown, MD, USA) was used to build a model consisting of the pelvis, thigh, shank and foot segments. The CODA model (Charnwood Dynamics Ltd., Leicestershire, UK) was used to construct the pelvis segment and the hip joint centre was derived using equations by Bell and Brand [28]. The sacrum marker was input as both the right and left posterior-superior iliac spine markers in Visual3D. The markers at the hip joint centre, and lateral and medial knee epicondyles, were used to define the frontal plane of the thigh segment. A virtual landmark was created by projecting the tibial tuberosity marker onto the plane created by the head of fibular, and lateral and medial malleoli markers. Using this virtual landmark, the frontal plane of the shank segment was defined as proximal joint centre and the mid-point of the lateral and medial malleoli markers as distal joint centre. Finally, a single-segment foot model was created using CAL2 as the proximal joint centre and the toe marker as the distal joint centre of the sagittal plane. CA1 was used to define the posterior orientation. For all the segments, the frontal plane determined the orientation of the X axis and the sagittal plane determined the orientation of the Y axis. The Z axis was orthogonal to both X and Y axes. Cardan/Euler rotation sequence was used for the knee joint angle calculation.

The motion and GRF data were filtered through a low-pass Butterworth digital filter at cut-off frequencies of 9 Hz and 50 Hz, respectively. Initial contact was defined as the first instant that vertical GRF exceeded 10 N. For each landing trial, two variables were calculated to indicate ACL injury risk: (1) KVA at initial contact, and (2) maximum KVM during the whole phase of landing. The whole landing phase was defined as twice the time taken from initial contact with the ground to the time of maximum vertical GRF, according to Dempsey et al. [20]. Maximum KVM was normalised to the product of each participant's height (m) and mass (kg) [20].

To verify that participants had landed in three distinct foot rotation positions as instructed, foot rotation angles at initial contact were measured with respect to the shank and also the pelvis.

2.5. Statistical analysis

The variables of interest include KVA at initial contact, maximum KVM and foot rotation angles. Values of the three trials per foot rotation condition were averaged and then used in statistical analysis. Normality assumption was first checked with the

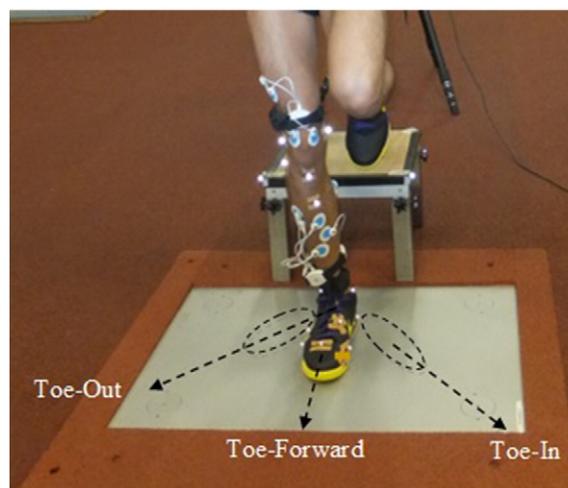


Figure 1. Three foot rotation positions: toe-out (away from the mid-line of the body), toe-forward, and toe-in (towards the midline of the body).

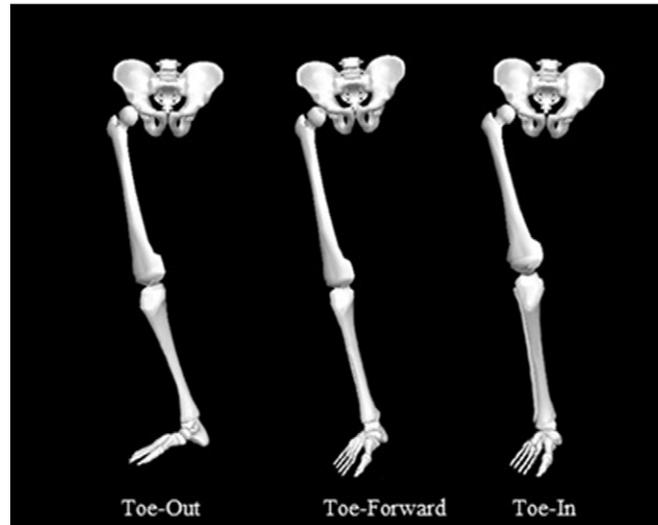


Figure 2. Representations of actual foot rotation positions that participants landed in: toe-out, toe-forward, and toe-in.

Shapiro–Wilk test ($p > 0.05$). If the data were not normally distributed, “reflect and logarithmic” transformation was applied. To compare among the foot rotation positions, a one-way repeated measures Analysis of Variance was conducted at $\alpha = 0.05$ (IBM SPSS 22.0 – IBM Corp., NY, USA) for each variable of interest. Assumption of sphericity was tested by Mauchly’s test of sphericity. When assumption of sphericity was not met, a Greenhouse–Geisser correction was applied. Post-hoc test with Bonferroni adjustment was made with a family-wise $\alpha = 0.05$. Effect size was calculated as η^2 and values of 0.01, 0.09 and 0.25 were interpreted as small, medium and large effects, respectively [29]. Data are expressed as mean (SD).

3. Results

Figure 2 illustrates the typical postures when participants were asked to land in toe-in, toe-forward, and toe-out positions. Foot rotation angles, when measured with respect to the shank, did not differ among the three foot positions ($p = 0.810$, Table 1). When measured with respect to the pelvis orientation, significant differences were noted ($p < .001$, Table 1). Post-hoc results showed that toe-in position was significantly less negative (i.e. less outward) than toe-forward position ($p = 0.004$). Similarly, toe-forward position was significantly less negative (i.e. less outward) than the toe-out position ($p < 0.001$).

Plotted over the entire landing phase, Figure 3 shows the mean ensemble curves of the vertical GRF, normalised to the body weight, KVA and KVM. There was a significant effect of foot position on KVA at initial contact ($p < .001$, Table 1). However, the actual difference in angles was small (toe-in vs. toe-forward: 1° , 95% confident intervals (CI) [0 to 1], $p = 0.001$; toe-in vs. toe-out: 1° , 95% CI [0 to 2], $p = 0.003$). Maximum KVM significantly differed among the three foot positions ($p < 0.001$, Table 1). Post-hoc tests showed greater KVM in the toe-out position, as compared to toe-forward ($p = 0.012$) or toe-in conditions ($p = 0.002$). No post-hoc difference in KVM was found between the toe-in and toe-forward positions ($p = 0.442$).

Table 1
Foot and knee biomechanics of toe-in, toe-forward and toe-out single-leg landings.

Variables ¹	Toe-in	Toe-forward	Toe-out	p-Value	η^2
Foot rotation angles ¹					
With respect to shank ($^\circ$)	6 (3)	6 (3)	6 (2)	0.810	0.02
With respect to pelvis ($^\circ$)	−10 (7) ^{bc}	−20 (5) ^{ac}	−30 (6) ^{ab}	<0.001	0.74
Knee valgus angles at initial contact ($^\circ$)	−2 (3) ^{bc}	−1 (3) ^a	−1 (3) ^a	<0.001	0.66
Maximum knee valgus moments ($\text{Nm kg}^{-1}\text{m}^{-1}$)	−0.60 (0.29) ^c	−0.67 (0.26) ^c	−0.82 (0.28) ^{ab}	<0.001	0.55

¹ Negative denotes toe-out or knee valgus directions. Effect sizes (η^2) of 0.01, 0.09 and 0.25 were interpreted as small, medium and large effects, respectively.

^a Significantly different from toe-in position.

^b Significantly different from toe-forward position.

^c Significantly different from toe-out position.

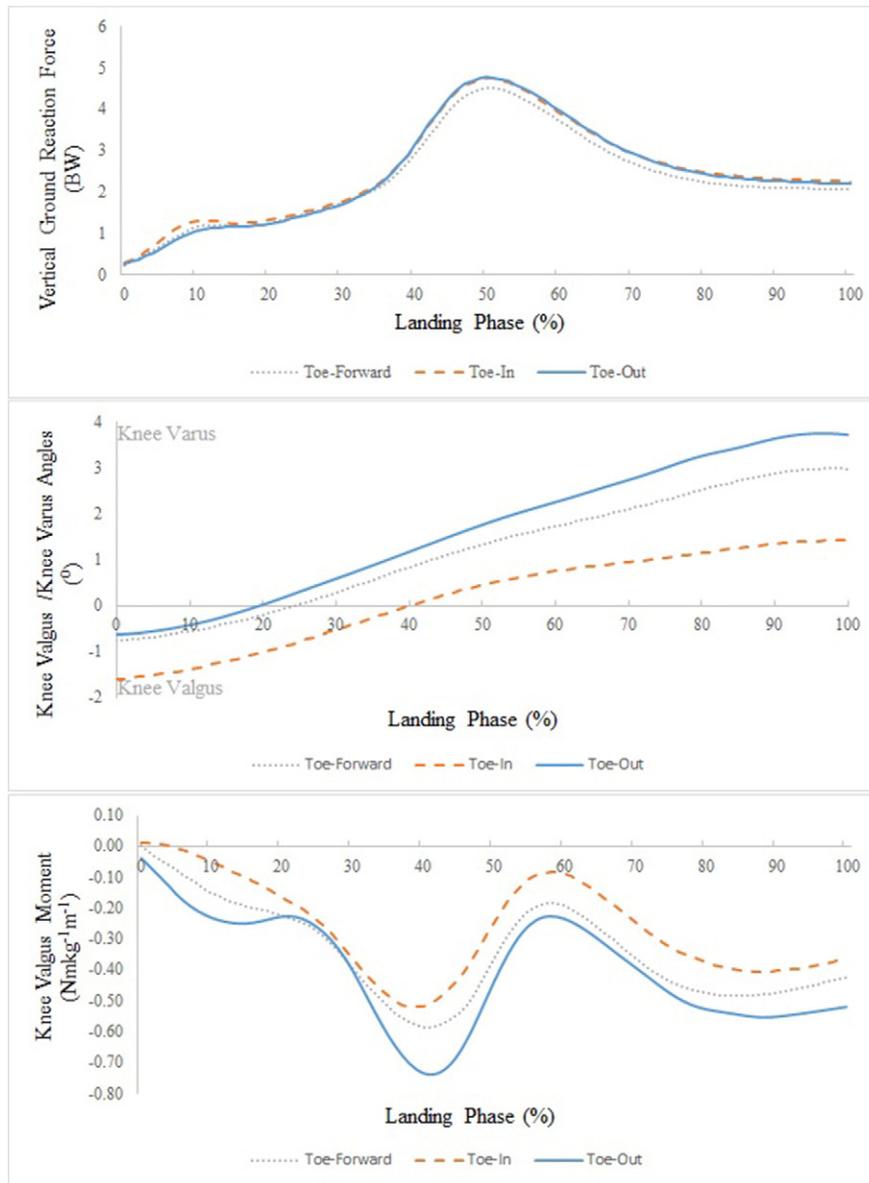


Figure 3. Mean vertical ground reaction force (normalized to the body weight (BW)), knee valgus angles and knee valgus moments (normalized to the product of height and body mass) under toe-forward, toe-in and toe-out foot rotation conditions. The whole landing phase was defined as twice the time taken from initial contact with the ground to the time of maximum vertical ground reaction force.

4. Discussion

The main objective of this study was to investigate the effects of foot rotation positions (toe-in, toe-forward, toe-out) on knee valgus during single-leg drop-landing. To our best knowledge, this is the first study to experimentally manipulate various foot rotation positions during single-leg landings. This provides a better understanding as to how knee biomechanics can be influenced by foot orientations. In support of our hypothesis, the toe-out position resulted in a significant increase in maximum KVM during landing. Foot rotation also had a significant effect on KVA at initial contact but the difference was too small to be practically meaningful.

4.1. Effects of foot rotation on KVM

The present study showed that toe-out foot rotation position resulted in significantly higher maximum KVM than toe-in and toe-forward positions. This finding confirmed the results of the study by Dempsey et al. [20] which found a significant correlation

between increased KVM and external foot rotation. Since higher KVM is associated with increased ACL injury risks [9,10,11], athletes should be advised to avoid landing in extreme toe-out positions during single-leg landing to minimise ACL injury risks. Given the lack of differences in KVM between the toe-in and toe-forward positions, landing within this range of foot rotation (about 10°, Table 1) would likely result in similar maximum KVM. These findings suggest that there is no detrimental effect on knee valgus loading when landed in a toe-in compared to toe-forward positions. Thus, it may not be necessary to emphasize the ‘toe-forward’ position as previously perceived [30].

During single-leg landings, the knees are generally at less than 20° of flexion at initial contact [31]. Within this range of small knee flexion angles, the “screw-home” mechanism can take place whereby the tibia externally rotates on the femur [32]. Furthermore, one previous study demonstrated that the toe-out foot rotation was associated with the tibia being more externally rotated with respect to the femur [21]. The medial collateral ligament (MCL) helps stabilise the knee joint by preventing it from going into knee valgus positions and by restraining external tibial rotation [33]. In the toe-out foot rotation position with more external tibial rotation, the MCL could have been twisted [34] such that it could buckle more easily to constrain less of KVM. This might in turn increase the loading of the ACL, which has the secondary role of restraining knee valgus/varus loading [35]. Thus, landing in a toe-out position may thereby increase ACL injury risks during single-leg landing.

The maximum KVM values (-0.82 to -0.60 Nm kg⁻¹ m⁻¹) obtained in our study were quite different from those reported in previous studies on single-leg landing using male subjects [20,36]. Dempsey et al. [20] obtained lower KVM mean values ranging from -0.43 (95% CI [-0.53 , -0.33]) to -0.23 (95% CI [-0.30 , -0.16]) Nm kg⁻¹ m⁻¹, for different landing tasks. Participants had to take off, catch a ball, and land with their preferred leg [20]. Their landing heights may differ from the fixed 30 cm in our study, resulting in lower range of KVM. On the other hand, Hong et al. [36] used a similar protocol of single-leg drop landing from a 30-cm platform and obtained a mean maximum KVM of -0.16 Nm kg⁻¹ m⁻¹, 95% CI [-0.20 , -0.13] using shod condition. Their different marker sets, especially without the use of the sacrum and anterior superior iliac spine markers, might have resulted in different maximum KVM values [36]. Since this study adopted a within-participant design, comparisons among the three foot rotation positions were made only within the same individual. Thus, the conclusion obtained would be robust regarding the influence of foot rotation positions, despite having different KVM values compared with previous studies.

4.2. Effects of foot rotation on KVA

This study also investigated the effects of foot rotation on KVA at initial contact and found significant but very small differences (-1° to -2°) among the three levels of foot rotation. Similar values of KVA were reported during single-leg landing (1° , 95% CI [-1 to 2]) [31], and in the video analysis of basketball games during initial contact (-3° , 95% CI [-2 to -4]) [5]. Despite the statistically significant difference and large effect size ($\eta^2 = 0.66$), the actual differences in angles are too small to be practically meaningful. Therefore, foot rotation does not substantially influence the risk of ACL injuries at initial contact of single-leg landings.

4.3. Foot rotation manipulation protocol

In the verification of foot rotation angles, foot rotation with respect to the shank did not differ among the three conditions. This suggests that the foot and shank tend to rotate together as one unit. Participants likely achieved the toe-in/out positions via internal/external rotations at the knee and hip joints. Ishida et al. [21] also demonstrated that toe-out foot rotation position resulted in a more externally rotated tibia with respect to the femur, whereas toe-in foot rotation position resulted in a more internally rotated tibia.

As shown in Table 1, the foot rotation angles with respect to pelvis progressively became more negative (outwards) from toe-in to toe-forward and then toe-out positions. It is interesting to note that all three foot rotation angles, including the toe-in position, were negative. This implies that despite the verbal instruction to land with various foot rotation conditions (Figure 1), participants all landed in negative, toe-out positions (Figure 2). This observation is somewhat unexpected; suggesting that toe-out foot rotation could be a natural landing position of these participants.

4.4. Limitations

There were a few limitations to our study. Firstly, only the dominant leg was examined in our study and future studies could also look at the non-dominant leg. With a higher reliance on the dominant leg, it may be exposed to higher forces and moments during high loading circumstances [37]. On the other hand, the non-dominant leg may be less trained to dissipate loading and moments [37]. Thus, both dominant and non-dominant legs can be susceptible to ACL injuries. Secondly, only foot rotation angles with respect to knee valgus were studied. A simultaneous manipulation of sagittal and frontal plane foot landing positions (e.g. [24]) could also be carried out. This could provide a more comprehensive understanding of foot-landing effects on non-contact ACL injury prevention. Thirdly, this study was carried out in a controlled laboratory environment using standardised drop-landing tasks. It is possible that the desirable effects of toe-in and toe-forward foot positions on maximum KVM might be less pronounced in actual playing conditions. A prospective intervention study could be conducted on a cohort, together with a control group, to provide insights as to whether the training of foot-landing techniques can help in reducing non-contact ACL injuries over a period of time.

5. Conclusions

This study showed that foot rotation positions can influence knee joint loading during single-leg drop landing. Specifically, landing in toe-out positions resulted in significantly higher maximum KVM compared with toe-in and toe-forward positions. Although foot rotation positions also influenced KVA at initial contact, the differences were too small to be clinically meaningful. When landing with one leg, athletes should avoid extreme toe-out foot rotation positions to minimise undesirable knee valgus loading associated with non-contact ACL injury risks.

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Conflicts of interest

The authors declare that there is no conflict of interest.

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