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Joint dynamics of rear- and fore-foot unplanned sidestepping

Cyril J. Donnelly[a,*,1], Chamnan Chinnasee[b,c,1], Gillian Weir[a], Siriporn Sasimontonkul[b], Jacqueline Alderson[a]

[a] School of Sport Science, Exercise and Health, The University of Western Australia, Australia
[b] Faculty of Sports Science, Kasetsart University, Thailand
[c] Faculty of Health and Sports Science, Thaksin University, Thailand

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ABSTRACT

Objectives: Compare the lower-limb mechanics and anterior cruciate ligament (ACL) injury risk of athletes using a habitual rear-foot (RF) and fore-foot (FF) fall pattern during unplanned sidestepping (UnSS).
Design: Experimental cross-sectional.
Methods: Nineteen elite female field hockey players attended one biomechanical motion capture testing session, which consisted of a random series of pre-planned and unplanned sidestepping sport tasks. Following data collection, participants were classified as possessing a habitual RF or FF fall pattern during UnSS. Hip, knee and ankle joint angles, moments, instantaneous powers and net joint work were calculated during weight acceptance. Between group differences were evaluated using independent sample *t*-tests ($\alpha = 0.05$).
Results: Athletes using a habitual RF fall pattern during UnSS absorbed significantly more work and power through their knee joint ($p < 0.001$), which was coupled with significantly elevated externally applied peak non-sagittal plane peak ankle moments ($p < 0.05$) as well as peak flexion and abduction knee moments ($p < 0.005$). Athletes using a habitual FF fall pattern during UnSS absorbed more power through their ankle joint ($p < 0.001$).
Conclusions: A RF fall pattern during UnSS places a large mechanical demand on the knee joint, which is associated with elevated ACL injury risk. Conversely, a FF fall pattern placed a large mechanical demand on the ankle joint. Modifying an athlete's foot fall pattern during UnSS may be viable technique recommendation when returning from knee or ankle injury.

1. Introduction

Single-leg landing or unplanned sidestepping (UnSS) have been identified as the dynamic movements where the vast majority of non-contact anterior cruciate ligament (ACL) injuries occur in sport.[1–4] The general mechanical aetiology of an ACL injury is when externally applied knee loads are elevated (e.g. peak anterior translation forces and combined knee moments) and muscle support is low.[5] Simulation research has shown that for an ACL injury event to occur during sidestepping, both abduction and externally applied flexion knee moments need to be present.[6,7] Research by Hewett et al.[8] has also shown peak valgus knee moments are predictive of ACL injury incidence in sport with 73% specificity and 78% sensitivity.

To develop effective countermeasures to reduce non-contact ACL injury risk in sport, much biomechanics research has focused on understanding the complex mechanical relationship(s) between athletes' movement and knee load patterns during single-leg landing and unplanned sidestepping. During planned sidestepping, relationships between an athlete's foot position relative to midline,[9,10] 'knee valgus angle (posture)',[9] hip mechanics,[10,11] arm position[12] and 'toe landing'[10] position have been related to peak abduction knee moments and ACL injury risk. From a comparatively small pool of UnSS research, Donnelly et al.[13] showed that an athlete's upper-body/trunk mechanics were critical kinematic variables related to peak abduction knee moments. In the same study, ankle dorsi/plantarflexion kinematics were also shown to be related to an athlete's peak abduction knee moments. As a validated foot-contact model was not used during the simulation process, conclusions relating to an athlete's ankle kinematics and

* Corresponding author.
E-mail address: cyril.donnelly@uwa.edu.au (C.J. Donnelly).
[1] These two authors should be recognised as first authors.

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subsequent ACL injury risk during UnSS were not made, leaving this relationship to be verified with future research.

A growing body of running literature has shown that the distribution of mechanical power and work between an athlete's ankle and knee is a function of their foot fall pattern (i.e. ankle kinematics) during the first half of stance.[14,15] Research has also shown that runners using a forefoot fall pattern (i.e., ankle plantarflexion) reported significantly lower peak abduction moments relative to runners using a rearfoot fall pattern (i.e., neutral or ankle dorsiflexion).[15,16] With limited *ex-vivo* biomechanics research investigating the relationship between foot fall patterns and lower limb mechanics during UnSS, it is unknown an athlete's foot fall pattern during UnSS influences an athlete's lower-limb mechanics and injury risk in sport.

The purpose of this study was to compare the lower-limb mechanics (i.e., hip, knee and ankle joint) of athletes who display habitual forefoot or rearfoot fall patterns during UnSS. We hypothesize differences in knee and ankle mechanics (i.e., joint kinetics – joint power and joint work) between athletes using a habitual rearfoot (UnSS-RF) vs. forefoot (UnSS-FF) fall pattern during the weight acceptance (WA) phase of UnSS. We further hypothesize that athletes using a habitual UnSS-RF fall pattern will display elevated peak abduction knee moments and ACL injury risk when compared with athletes possessing habitual UnSS-FF fall patterns.

2. Methods

Nineteen elite female field hockey players participated in this study (22.2 ± 2.9 yrs, 1.7 ± 0.1 m, 62.9 ± 7.1 kg). This sample was representative of all athletes listed on the Australian the Female Field Hockey team roster who were deemed fit, healthy and injury free by the team's medical staff (i.e., team physiotherapist or team doctor) prior to testing. The reason an elite female population was chosen for this investigation is because previous literature has shown this cohort is at a risk of ACL injury when compared with males[17] and less experienced players of the same sex.[18] When comparing the total number of NCAA soccer related ACL injuries between women and men from 1994 to 1998, women were shown to have injury rates 2.8 times higher than their male counterparts.[17] When compared to novice athletes, experienced females display significantly elevated peak valgus knee moments ($p = 0.01$) during sidestep cutting sporting tasks (0.4 ± 0.5 vs. 0.9 ± 0.6Nm/kg × BW respectively).[18] All participants provided their informed written consent prior to data collections. Ethics approval was obtained from the Human Research Ethics Office at the University of Western Australia (UWA) (RA/4/1/5713).

All participants attended a single motion capture testing session. During this testing session athletes were instructed to wear their normal training attire, which consisted of a sports bra, singlet, form fitted shorts and their team shoes. The shoes each athlete wore for testing were all the ASICS women's gel-Kayno 21 (Kogan, Australia Pty Ltd.). All participants completed the previously published UWA sidestepping protocol, which consisted of a random series of pre-planned and unplanned straight run, crossover and change of direction (i.e., sidestepping) sporting tasks using their self-selected preferred leg.[19,20] Participants completed five successful trials of each sporting task before testing was complete. Three-dimensional full-body kinematics were recorded using a 12-camera Vicon MX system (Oxford Metrics, Oxford, UK) recording at 250 Hz, synchronised with a 1.2 m × 1.2 m force plate (AMTI, Watertown, MA) sampling at 2000 Hz. Kinematic and ground reaction force data were both low pass filtered with a zero-lag fourth order Butterworth filter at 14 Hz, which was determined following residual analysis and visual inspection.[21,22] These data, with functional hip joint centres and knee joint axes[23] and a custom lower body kinematic model in Bodybuilder (Vicon Peak, Oxford Metrics Ltd., UK), were used to calculate lower limb kinematics and kinetics via inverse dynamics from an established biomechanical model with established repeatability.[23] A full description of the experimental procedures and kinematic and kinetic modelling approaches have been described previously.[15,20]

Following data collection, participants were initially classified as possessing a natural habitual rear-foot (RF) or 2) habitual forefoot (FF) fall pattern during UnSS from their motion capture data (Fig. 1). Borrowing from the running literature, a RF fall pattern was defined as when the rear of the foot segment made initial contact with the ground at 0% of stance and a FF fall pattern when the front of the foot made initial contact with the ground at 0% of stance.[24] The vertical ground reaction force vector was used to define 0% and 100% of stance, which was when the vector was greater than and less than 10 N, respectively.

Following the initial classification of each athlete's foot fall pattern, their ankle joint plantar/dorsi flexion angles were calculated for each individual UnSS trial. Participants were removed if they did not consistently use the same foot fall pattern for all five of the UnSS trials collected in lab. This left nine (47%) participants (1.7 ± 0.1 m, 63.9 ± 6.4 kg) classified as possessing a habitual UnSS-RF fall pattern and seven (37%) participants (1.7 ± 0.1 m, 62.0 ± 7.6 kg) classified as possessing a UnSS-FF fall pattern (see Table 1 and Fig. 2). The approach velocity of the participants within the UnSS-RF (4.3 ± 0.5 ms^{-1}) and UnSS-FF (4.3 ± 0.2 ms^{-1}) were compared using an independent sample t-tests and were not significantly different ($p = 0.81$) from each other.

Mean hip, knee and ankle joint angles, moments, instantaneous power and net joint work were calculated from five UnSS trials during the weight acceptance phase of stance. Kinematic estimates

Table 1
Joint kinematics for habitual UnSS-RF and UnSS-FF at initial foot contact (0% stance) and range of motion (RoM) through WA.

Kinematic variable	UnSS-RF ($n = 9$)	UnSS-FF ($n = 7$)	p	Power ($1 - \beta$)
Angle at 0% stance (°)				
Ankle plantar/dorsi flexion	***7.1 ± 8.5***	***16.0 ± 6.5***	***<0.001***	***1.00***
Ankle Ab/Adduction	***−7.1 ± 4.5***	***−15.2 ± 5.8***	***0.007***	***0.89***
Ankle inversion/eversion	−8.0 ± 9.8	0.7 ± 7.2	0.070	
Knee flexion/extension	18.2 ± 6.3	18.2 ± 6.8	0.988	
Hip flexion/extension	***58.7 ± 6.8***	***48.8 ± 6.3***	***0.010***	***0.77***
RoM through WA (°)				
Ankle plantar/dorsi flexion	***20.5 ± 1.8***	***35.6 ± 7.9***	***<0.001***	***1.00***
Ankle Ab/Adduction	9.3 ± 3.0	8.1 ± 6.2	0.636	
Ankle inversion/eversion	37.5 ± 6.1	33.8 ±5.9	0.252	
Knee	37.5 ± 6.1	33.3 ± 4.8	0.160	
Hip	10.7 ± 4.8	7.2 ± 3.1	0.121	

Note: positive values indicate knee flexion, hip flexion, ankle dorsiflexion, ankle adduction and ankle inversion.
Bold and italicized significance was set to an $\alpha = 0.05$.

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