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ASSESSMENT OF PATTERNS AND VARIABILITY IN LOWER EXTREMITY COORDINATION BETWEEN GENDERS WITH DIFFERENT SHOE INSOLE STIFFNESS DURING JUMP-LANDING TASKS

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ABSTRACT
Purpose. The study aims to examine how shoe insole cushioning can influence coordination pattern and variability in males and females during the landing phase of a jump-landing task.
Methods. Twenty participants (10 males and 10 females) performed jump-landing tasks, and the continuous relative phase (CRP) and the variability of CRP in foot-shank and shank-thigh couplings were determined during the landing phase.
Results. Women represented lower CRP and CRP variability of foot-shank coupling in non-insole conditions ($p < 0.05$). Shoe insole stiffness had no significant effect on CRP or variability in CRP ($p > 0.05$).
Conclusions. Although females are characterised by lower coupling variability in non-insole conditions, they do have the capacity to achieve similar coordination patterns and variability as males, in soft and hard conditions. These findings suggest that with changes in the shoe insole, females can achieve similar joint coupling coordination patterns and variability as compared with males under soft and stiff conditions. In addition, as per this study, changes in shoe insole stiffness may not have an impact on coordinative strategies or variability of lower extremity joints couplings during landing.
Key words: coordination, variability, continuous relative phase (CRP), gender, jump-landing, shoe insole

Introduction

Many sports and movement activities contain a jumping component, which in turn involves landing. During landings, mechanical loads may be exerted onto the lower extremity joints, causing injuries such as stress fracture [1], patellar tendinopathy [2], anterior cruciate ligament (ACL) injury [3, 4], and ankle sprains [5] in both female and male athletes involved in repetitive landing activities. Evidence suggests that females are more likely to suffer from landing-related injuries in the lower extremity, such as ACL rupture and patellofemoral pain syndrome [6]. Altered neuromuscular control during landing has been identified to increase the risk of lower extremity injuries in females as compared with males [6, 7].

Different shoe conditions can potentially modify the mechanical load transferred to the musculoskeletal system [8] and adjust joint kinematics resulting from foot-ground impact [9]. Modifications in shoe stiffness have been investigated as a mechanism to prevent lower extremity injuries during landing [9, 10]. But the majority of studies on footwear and lower extremity joints have reported on individual joint action rather than coordination between joints [8, 9]. The integrative movement of one joint with respect to another i.e. coordination, may provide insights into the relationship between lower extremity joints and, consequently, the possible loading on the stabilizing structure of lower limb joints [11]. Several studies have concluded that coordination and variability in coordination provide the flexibility required during movement and adaptation to changes in the environment [12, 13]. Stergiou and Bates [14] showed that peak foot eversion should occur at the same time as maximal internal tibial rotation and maximum knee flexion; the lack of timing between these actions has been suggested as a possible mechanism for knee pain in runners. In addition, Miller et al. [15] proved that lack of synchrony between thigh abduction/adduction and tibial external/internal rotation couplings might be related to the iliotibial band syndrome in runners. However, hardly any effort has been made towards investigating these adaptive strategies during jump-landing tasks or their relation to different shoe insole hardness.

Footwear or shoe insole stiffness may be a control parameter that results in new coordinative strategies. Kurz and Stergiou [16] reported that ankle coordinative strategies were significantly different between various shoe stiffness and barefoot running conditions, and might

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be related to mechanisms that alter impact force during running. Examining the coordinated action of lower extremity segments in space and time in response to the alternation of footwear provides insights that traditional time series plots of segment motions cannot offer. Limited studies have examined gender differences in the movement patterns of lower limb joints during landing [3–4]. Pollard et al. [17] reported that females demonstrated decreased variability in coupling motions of lower extremity joints during a cutting manoeuvre, which may be associated with increased incidence of ACL injury in women.

However, there would appear to be no investigation that reports on the coordination pattern of lower extremity differences between males and females and how they relate to shoe cushioning during dynamic activities such as jump-landing. Therefore, the purpose of the study was to examine how insole stiffness influenced coordination patterns and variability in lower extremity joints during landing, and how this differed between males and females.

Material and methods

Participants

The participants were 20 university students, comprising 10 men (mean ± *SD*; age: 21.33 ± 2.42 years; height: 180.5 ± 10.00 cm; mass: 69.08 ± 7.67 kg) and 10 women (mean ± *SD*; age: 21.00 ± 1.32 years; height: 165.5 ± 9.00 cm; mass: 59.08 ± 7.67 kg) who had engaged in competitive sport activities that included jump-landing manoeuvres (such as basketball and volleyball) for the past three years. The following inclusion criteria were applied: no history of orthopaedic lower limb problems, neurological disease or cardiovascular pathology. The sample size was determined to be large enough to detect significant differences between different conditions. The number of subjects was calculated with the use of SPSS Sample Power 3.0 (SPSS Inc., Chicago, IL, USA) and based on the effect size (*ES*) of 0.25 standard deviation (*SD*), with an alpha level of 0.05, and power at 0.80. All the subjects provided their informed consent, and the study was approved by the university review board.

Procedure

All the participants were familiarized with the testing procedure. A standardized general warm-up was performed, followed by dynamic stretching exercises consisting of approximately 15 seconds for each muscle group. The subjects performed two tasks: a maximum vertical jump (MVJ) test and a jump-landing task. To measure the MVJ, the highest standing hand reach was subtracted from the jump, as well as the highest reach of the subject (Sargent jump test). The MVJ test was used to set the main testing protocol of the jump-landing task. During this, the participants jumped forward and upward in an attempt to hit a suspended soccer ball and then land with both feet in the centre of two force plates flush with the ground; this was followed by jumping as high as they could straight up in the air and finally landing back onto the force plates. The first landing phase (from the instant of initial contact [IC] to take-off) was used in data analysis. The starting position for each participant was 50% of height from the centre of the suspended ball. The distance from the centre of the force plate to the vertically suspended ball was 50% of MVJ (Figure 1). All the participants were instructed on the proper jumping mechanics, including landing softly with feet approximately shoulder-width apart, maintaining the alignment of knees over toes and shoulders over knees, and stabilizing in a partial squat position. The subjects were allowed to practice the jumps until they reported feeling comfortable with the task and were able to perform repetitions with the proper technique.

Each participant performed five successful jump-landing trials. The results of five trials were averaged and used for statistical analysis. The order in which the shoes were tested was randomly assigned for each subject. All

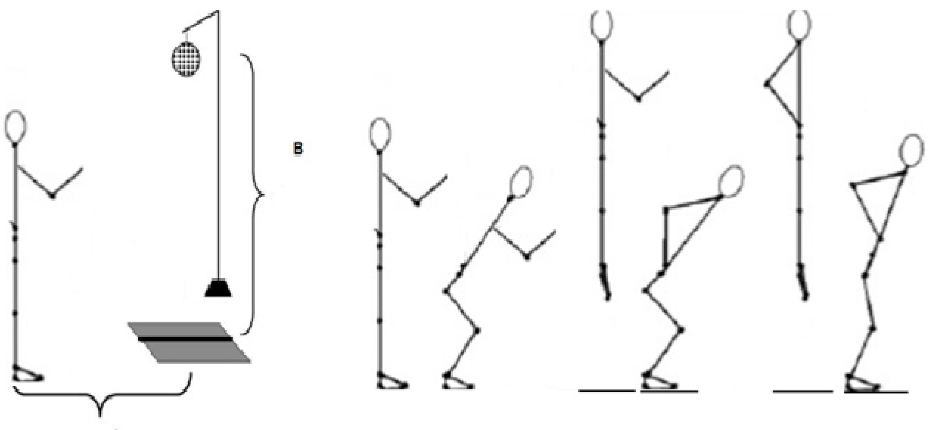


Figure 1. A diagram of the jump-landing task (right) and experimental set-up for the jump-landing task (left).
A. The distance from the starting position to the centre of the force plate is 50% of the participant's height.
B. The distance from the centre of the force plate to the soccer ball is 50% of the maximum vertical jump height

of them performed jump-landing trials with the same sports shoes (sneaker model, Nike Air Max Glide) that were supplied by the investigators in the study. Three shoe conditions were investigated, differing only in terms of insole stiffness: Asker C-40 (soft), Asker C-65 (stiff), and non-insole. The compliance of insoles was based on the manufacturing test. The insoles were constructed of polyurethane foam moulded into the shape of a foot bed (6-mm thickness at the centre of the heel and 3-mm thickness at the forefoot) with a textured Poron foam top cover (1-mm thickness).

Experimental set-up

Coordinates of retro-reflexive markers (14 mm in diameter) were sampled at 200 Hz with an eight-camera optical motion capture system (Oqus 300, Qualisys, and Gothenburg, Sweden). Ground reaction force (GRF) values were sampled synchronously at 1000 Hz with the use of two force platforms (ORS model, AMIT, Watertown, MA, USA) embedded in the lab surface. Cameras positioned around the two force plates captured the participants' jump-landing tasks. Markers were placed bilaterally over the following landmarks: fifth metatarsal head, calcaneus, lateral malleolus, and lateral epicondyles of knee, lateral thigh, posterior superior iliac spine, and anterior superior iliac spine [18]. For the purpose of the study, only the right side was used for data reduction and analysis. Prior to data collection, a static calibration trial was collected with the subject in a quiet stance.

Data analysis

Qualisys Track Manager (Qualisys Inc., Gothenburg, Sweden) was used to track the positions of the markers and to process raw marker data. Marker coordinates were filtered with a fourth-order Butterworth filter. The cut-off frequency for low-pass filtering of kinematic data was 12 Hz, as determined with a residual analysis [19].

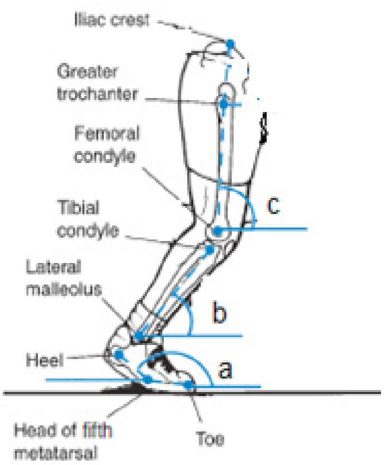


Figure 2. The definition of absolute angles of foot (a), shank (b), and thigh (c) in a sagittal view [19]

In the present study, frames associated with IC of the first landing and take-off were established for the start point and end point, respectively. The IC of the landing phase was defined as the instant where the force plate reported values greater than 20 N [20].

Sagittal plane segmental angles relative to the right horizontal (θ) were calculated for the thigh, shank, and foot (Figure 2). Segmental angular velocities (ω) were calculated with the first central difference method. The time series for each segmental angle and angular velocity were plotted for the first landing (from IC to take-off). To determine the coordination, the continuous relative phase (CRP) method was implemented for foot-shank and shank-thigh couplings [21]. Figure 3 illustrates the process by which CRP was calculated for the right thigh-shank coupling during the landing phase.

Phase plots were calculated for the relevant segment and joint angles. Each phase plot consisted of the angle (θ) on the horizontal axis, with its first derivate, angular velocity (ω), on the vertical axis. To calculate the phase angle (φ), phase plots were normalized for each trial. The phase angle was defined as the angle between the right horizontal axis and a line drawn from the origin to a specific data point (θ, ω), and was calculated as follows:

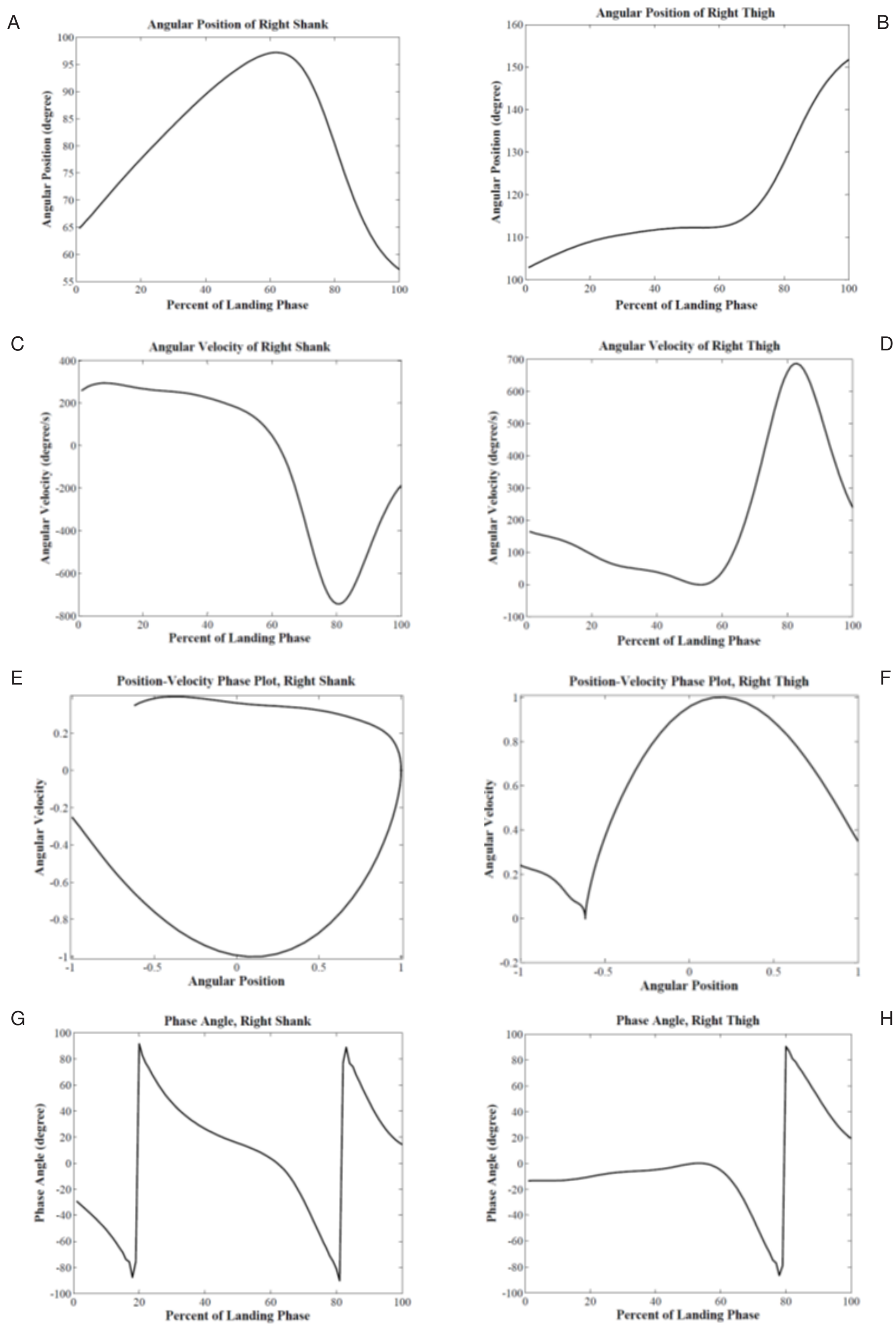
$$\varphi = \tan^{-1} \frac{\omega(t)}{\theta(t)}$$

CRP was then calculated for foot-shank and shank-thigh couplings in the sagittal plane by subtracting the relative phase of the distal segment from the proximal segment.

$$\mathrm{CRP}(t) = \varphi(t)\textit{proximal segment} - \varphi(t)\textit{distal segment}$$

To measure the mean CRP and CRP variability, the CRP profile for each coupling relationship was interpolated to 100 data points with the use of the polynomial procedure. Ensemble curves were calculated from the coupling relationships for each participant, as the mean from five trial CRP curves. The mean and variation of CRP were calculated as the *SD* of each point on the ensemble curve, and quantified by calculating the average *SD* over the complete profile.

The normality was assessed with the Kolmogorov-Smirnov test. Two-way repeated measures analyses of variance (3 insole stiffness × 2 genders) were performed on the CRP and CRP variability during landing. Statistical analysis was carried out for each joint coupling (foot-shank and shank-thigh). To quantify meaningfulness, the *ES*s were also calculated with Cohen's *d*. All statistical analyses were performed with SPSS 18.0 (SPSS Inc., Chicago, IL, USA), and the significance level was set as $p < 0.05$.



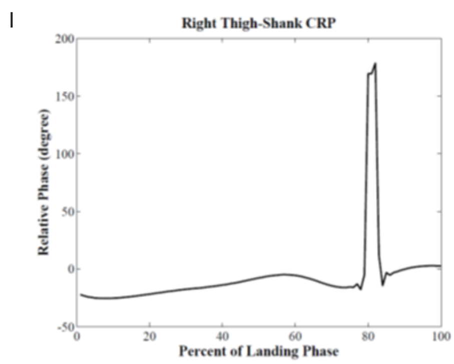


Figure 3. An example illustration of the process by which the continuous relative phase (CRP) was calculated from thigh-shank angles and angular velocity segments. A, B. Time series of the shank and thigh angular position during the first landing phase (from initial contact to toe-off). C, D. Time series of the shank and thigh angular velocity during the first landing phase (from initial contact to toe-off). E, F. Angular position-Angular velocity phase plots were created for the landing phase. These phase plane data were then normalized on the basis of maximum joint angles and angular velocity. G, H. Phase plane data were then converted to phase angle data for each point along the landing phase. I. Thigh phase angles were subtracted from the shank phase angles to form the thigh-shank CRP values for each point, and interpolated to 100% of the landing phase with a cubic spline function

Table 1. CRP and CRP variability of foot-shank and shank-thigh couplings for males and females during the landing phase in stiff insole conditions

	Males		Females	
Joints coupling	CRP (°)	CRP variability (°)	CRP (°)	CRP variability (°)
Foot-shank	9.3	65.10	11.15	63.8
Shank-thigh	25.6	40.0	23.3	38.8

Table 2. CRP and CRP variability of foot-shank and shank-thigh couplings for males and females during the landing phase in non-insole conditions

	Males		Females	
Joints coupling	CRP (°)	CRP variability (°)	CRP (°)	CRP variability (°)
Foot-shank	20.13*	65.1	17.8	72.3
Shank-thigh	22.6*	42.2	26.4	40.5

* Statistically significant difference as compared with females, $p < 0.05$

Table 3. CRP and CRP variability of foot-shank and shank-thigh couplings for males and females during the landing phase in soft insole conditions

	Males		Females	
Joints coupling	CRP (°)	CRP variability (°)	CRP (°)	CRP variability (°)
Foot-shank	22.63	67.1	6.2	69.2
Shank-thigh	26.7	40.5	17.6	40.2

Results

No significant differences in CRP values ($p = 0.26$) or variability in CRP ($p = 0.13$) were found between the shoe conditions for foot-shank coupling (Tables 1–3).

During landing, women demonstrated significantly lower CRP ($p = 0.00$, $ES = 0.52$) and CRP variability ($p < 0.01$) in foot-shank coupling. *Post hoc* testing showed significant differences in the non-insole condition ($p = 0.045$, $ES = 0.6$); however, these differences were not significant for stiff and soft insole conditions.

No interaction was found between gender and the shoe condition in terms of CRP values ($p = 0.34$) and variability in CRP ($p = 0.43$) for foot-shank coupling.

CRP and CRP variability were not influenced by shoe condition differences ($p = 0.66$ and $p = 0.13$, respectively), gender differences ($p = 0.61$ and $p = 0.36$, respectively), or shoe stiffness and gender interaction ($F = 0.79$, $p = 0.45$ and $p = 0.43$, respectively) in shank-thigh coupling (Tables 1–3).

Discussion

The purpose of the study was to determine how shoe cushioning can influence coordination patterns and variability in lower extremity joint couplings between males and females. The results of the investigation indicate that gender differences exist in the coordination pattern of foot-shank coupling in the sagittal plane, but these coordinative strategies are not influenced by shoe insole cushioning. Furthermore, females and males have different patterns of foot-shank coupling during non-insole conditions, but the coordination patterns and variability in foot-shank and shank-thigh couplings in stiff and soft insole conditions were similar between genders. These results are in agreement with previous studies [22, 23], indicating that females and males have different joint coupling coordination patterns during landing. A key extension over previous studies included the fact that the current task studied jump-landing. The study proves that women display less foot-shank coupling coordination and variability. Previous studies suggested that the decreased variability of joint couplings might be attributed to less flexible coordination, which could indicate less adaptability of lower extremity joints to the changes in the environment, and increase the risk of injuries. For example, it is well-known that women encounter non-contact ACL injuries more often than men during landing activities [17]. This may be related to the less flexible pattern of coordination, which limits their ability to adapt to the environmental perturbations, frequently experienced during jump-landing activities. In addition, a comparison of gender differences in landing mechanics may provide further insight into coordination and variability differences. Previous studies have reported kinematic landing pattern differences between genders at IC [24, 25].

A low CRP value indicates that there is a more coordinated relationship (in phase) between two segments, whereas a high CRP value demonstrates a lower coordination (out of phase) interaction between segments. Therefore, although females may inherently possess lower coupling variability than males, they have the capacity to achieve similar coordination patterns and coordination variability under insole conditions.

The results of present study demonstrated similar coordination patterns and variability for foot-shank and shank-thigh couplings between hard, soft, and non-insole conditions. The findings indicate that lower extremity coordinative strategies are not affected by footwear conditions. Kurz and Stergiou [16] applied the dynamic system theory to explore ankle coordinative strategies under bare-foot, hard, and soft shoe conditions. The results of their study revealed significant differences in CRP between shoe insole and bare-foot conditions during treadmill running. These differences in coordination strategies were attributed to the different mechanical roles of the surrounding ankle musculature during bare-foot running. Besides, during bare-foot running, the lower extremity perception of impact forces, gained through mechanoreceptors, may also affect coordinative strategies. Kurz and Stergiou [16] found no significant differences in the coordination of sagittal foot-shank and foot-leg couplings between the two shoe conditions. They suggested that the ankle might not have sensed a need to change the coordinative strategies. Moreover, Lake and Lafortune [23] pointed out that individuals could not perceive small changes in material densities. The current study supports similar findings in that the change in shoe insole stiffness may not have been sufficient for changes in the coordinative strategies. An alternative explanation is that the participants were athletes involved in sports activities that included jump-landing manoeuvres and performed a highly controlled jump-landing task. They were instructed on the proper jumping mechanics, such as landing softly with feet approximately shoulder-width apart, maintaining alignment of knees over toes and shoulders over knees, and stabilizing in a partial squat position. These constraints may potentially reduce the available degrees of freedom (or redundancy) and limit the differences in joint coupling variability between shoe conditions.

Conclusions

The investigation provides insights into how shoe insole stiffness affects joint coupling coordination, as well as coordination variability between genders. The results indicate that coupling coordination and coordination variability in non-cushioned shoe conditions are lower for females as compared with males. Gender differences in coordination and variability may provide insights into the reasons behind injury risk differences between males and females. However, in the case of stiff and soft insole conditions, both genders demonstrated similar coordination and variability in coordination. These findings suggest that with changes in the shoe insole, females may gain the capacity to achieve a similar joint coupling coordination pattern and variability as male athletes, under both soft and stiff insole conditions. Therefore, while females may inherently possess lower coupling variability than males, they can achieve similar coordination as their male counterparts with the necessary insole modification. It is also possible that changes in shoe insole hardness in the current study was not sufficient to initiate modifications in coordinative strategies and coordination variability in lower extremity joint couplings.

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