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Gender differences in coordination variability between shank and rearfoot during running

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ABSTRACT

Female recreational runners are 2–3 times more likely to suffer from knee injury compared with male runners. However, the exact reason for this gender difference regarding knee injury remains unclear. Our study aimed to investigate gender differences in coordination variability between shank and rearfoot during running using statistical parametric mapping (SPM). Eleven healthy males and eleven healthy females ran on a treadmill. A modified vector coding technique procedure was used to create joint coupling between shank internal/external rotation and rearfoot eversion/inversion. The standard deviation of each coupling was computed as a measure of coordination variability during the stance phase. All trajectory data of coordination variability between genders were analyzed using a two-sample *t*-test of SPM. No differences in the normalized spatiotemporal parameters of speed, cadence and step length were found between males and females. SPM showed no significant differences between the genders in coordination variability. This study demonstrated that coordination variability between the shank and rearfoot during running may not be associated with the different incidence rates of knee injuries among male and female participants.

1. Introduction

Running is a simple exercise with many beneficial effects. However, the incidence of running injuries is alarmingly high. A previous study (Lun, Meeuwisse, Stergiou, & Stefanyshyn, 2004) showed that at least one lower limb injury was experienced by 79% of all runners. Majority of running injuries occur in the knee joint (Taunton et al., 2002), and female recreational runners are 2–3 times more likely to experience patellofemoral pain (PFP) compared with males (Boling et al., 2010; Robinson & Nee, 2007). Altered lower extremity mechanics, such as knee joint motion during tasks, has been observed between runners with and those without PFP (Willson & Davis, 2008) or with PFP in males and those in females (Nakagawa, Serrao, Maciel, & Powers, 2013), which is thought to be related to the etiology or exacerbation of patellofemoral joint symptoms. Similarly, some studies have also investigated knee joint kinematics during running to identify the reason for gender difference in knee injury rates. For example, healthy female runners demonstrated a significantly greater peak knee internal rotation and ankle eversion than healthy male runners, and excessive motions of knee and ankle joint have been suggested to be involved in the incidence of running injuries in females (Ferber, Davis, & Williams, 2003; Sinclair & Taylor, 2014).

While the findings from previous investigations are of interest, they reduced time series data to a discrete kinematics, which may

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in turn fail to capture the complex dynamics nature of the movement (Pollard, Stearns, Hayes, & Heiderscheit, 2015). As an alternative approach to examining human movement, coordination variability could be investigated by a dynamics system approach. Coordination variability has been suggested to be a critical index for defining both the state of injury and the potential risk of injury (Hamill, Palmer, & Van Emmerik, 2012). In a healthy state, a person has many available individual degrees of freedom that could be combined or coordinated to achieve a movement task. Hence, a low variability means less flexibility of the body to adapt to changing situations, which may in turn lead to greater repetitive stresses on the joint. Moreover, extreme variability in a coupling motion also suggests compromised neuromuscular control, which may be indicative of a potential injury (Hamill et al., 2012).

The cross-correlation coefficient between shank internal rotation/external rotation (IR/ER) and rearfoot eversion/inversion (EV/IN) was high during running ($r = 0.95$), suggesting that running requires strong kinematic coupling of the shank and rearfoot (Pohl, Messenger, & Buckley, 2007). Furthermore, this coupling may play a significant role in impact force attenuation (Hintermann, Nigg, Sommer, & Cole, 1994). Cunningham, Mullineaux, Noehren, Shapiro, and Uhl (2014) reported that variability between shank IR/ER and rearfoot EV/IN in PFP runners is greater than that in healthy runners. Moreover, coordination variability assessment has been suggested to be useful for detecting even the risk factor for running injuries (Hamill et al., 2012). It is possible that a difference in coordination variability between healthy male and female individuals may be detected because of females are high knee injury rates than males (Boling et al., 2010). However, a recent study (Boyer, Freedman Silvernail, & Hamill, 2017) showed that variability between shank IR/ER and rearfoot EV/IN during running is not significantly different between healthy younger males and females. In addition, other previous studies (Hafer, Brown, & Boyer, 2017; Silvernail, Boyer, Rohr, Bruggemann, & Hamill, 2015) have also not found any difference between groups (younger versus older, or with versus without iliotibial band syndrome).

Previous studies (Hafer et al., 2017; Silvernail et al., 2015) have had limitations. First, despite coordination variability is continuous trajectory data, previous studies have averaged variability data during sub-phases (early, mid, and late stances). If variability is averaged in the sub-phase, the standard deviation of the variability becomes large and variability differences between groups may be difficult to detect. Second, because discrete parameter extraction of coordination variability (Boyer et al., 2017; Hafer, Freedman Silvernail, Hillstrom, & Boyer, 2016) is limited to specific events, other trajectory data regarding coordination variability are not assessed. However, in the case of traditional statistical analyses, such as the independent *t*-test applied to trajectory data at each time point, the risk of type I errors may be increased. To mitigate these limitations of analyses, statistical analysis methods exploring the entire movement trajectory, such as statistical parametric mapping (SPM), have been suggested (Pataky, 2010; Pataky, Robinson, & Vanrenterghem, 2013).

This study aimed to investigate gender differences in coordination variability between transverse shank angle and frontal rearfoot angle during running using SPM. Female runners are more likely to experience PFP compared with male runners (Boling et al., 2010), and coordination variability assessments have been suggested to be useful for detecting risk factors for running injuries (Hamill et al., 2012). In addition, previous studies (Cunningham et al., 2014; Dubbeldam, Nester, Nene, Hermens, & Buurke, 2013) have averaged coordination variability during the sub-phase. Moreover, variability differences between groups may be difficult to detect. Because this study applied SPM to all trajectory data of coordination variability, we hypothesized that differences in coordination variability between the shank and rearfoot for male and female runners can be detected. The results of this study may provide new insight into analyzing coordination variability.

2. Methods

2.1. Participants

Eleven healthy males (age = 20.5 (1.1) years; height = 1.72 (0.06) m; mass = 65.9 (7.7) kg) and eleven healthy females (age = 20.5 (1.0) years; height = 1.60 (0.07) m; mass = 52.5 (8.1) kg) participated in this study. All participants jogged approximately once or twice per week. Recent study (Floría, Sánchez-Sixto, Ferber, & Harrison, 2018) has stated that levels of experience had little influence on coordination variability. Inclusion criteria were as follows: no history of or current lower limb injuries and normal foot based on the arch height index during 90% weight bearing. The arch height index was calculated by dividing the arch height at 50% of the foot length by the truncated foot length (distance from the first metatarsophalangeal joint to the heel). The reference value for the normal foot was 1.5 standard deviations (SD) above or below the mean arch ratio measurement of 0.292 (SD 0.027) (Williams & McClay, 2000), which was based on a previously examined sample population of 102 feet (Williams, McClay, & Hamill, 2001). In our study, all participants provided written informed consent before participation. This study was approved by the ethics committee of our institution (No. 17724-160902).

2.2. Experimental protocol

Reflective markers (9.5 mm in diameter) were fixed to the right shank and foot at the tibial tuberosity, fibula head, medial malleolus, lateral malleolus, Achilles tendon attachment (calcaneus), sustentaculum tali, peroneal tubercle, navicular bone, cuboid, first metatarsal base, first metatarsal head, second metatarsal base, second metatarsal head, fifth metatarsal head, and head of the proximal phalanx of the hallux, which was based on a previous study from Leardini et al. (2007) and whose reproducibility has been confirmed in another previous study (Seo et al., 2014). Additionally, a marker was attached to the right posterior superior iliac spine. The posterior superior iliac spine marker was used to determine the stance phase with calcaneus and second metatarsal head markers.

The participants performed barefoot running on a treadmill (Auto Runner AR-100: Minato Medical Science, Osaka, Japan). Several previous studies (Almonroeder & Benson, 2016; Boyer et al., 2017; Chumanov, Wall-Scheffler, & Heiderscheit, 2008; Ferber et al., 2003) have had male and female participants run at the same speed (e.g., 4.0 m/s ± 5%). However, if the same running speed is applied to both males and females, females are likely to increase their step length and cadence parameters compared with males because women are generally smaller in body size, which may ultimately affect shank and rearfoot coordination. Therefore, the running speed was determined based on the protocol of a previous study (Pohl et al., 2007). First, participants walked barefoot at a self-selected speed on the treadmill. Next, the experimenter gradually increased the treadmill speed every 0.2 km/h. Participants were instructed to maintain a walking gait until they could no longer refrain from running. The point at which they started running was set as the treadmill speed (jogging). This protocol enabled the experimental speeds for each subject to be standardized. Finally, all spatiotemporal parameters were normalized as follows: speed normalized by the square root of the acceleration of gravity × leg length; cadence normalized by the square root of the leg length/acceleration of gravity; and step length normalized by leg length (Hof, 1996; Takabayashi et al., 2017).

Prior to measurement of running task, participants were asked to stand upright with double-leg support, and static standing data were measured. The participants were allowed to practice the tasks repeatedly for > 1 min on the treadmill. The experimenter questioned the participants to confirm whether they were accustomed to the motion. After all subjects verbally reported feeling comfortable while running on the treadmill, the stance phases of five right-side strides were measured for each participant. The static standing data and task were measured using a three-dimensional motion analysis system (Vicon, Oxford, United Kingdom) that included 13 infrared cameras at a sampling rate of 250 Hz.

2.3. Data analysis

Raw marker trajectory data during running were filtered using a second-order, zero-lag Butterworth low-pass filter with a 12-Hz cut-off frequency. The shank and rearfoot were modeled as rigid segments, according to the study of Cappozzo et al. (1995) and Leardini et al. (2007), respectively. Three-dimensional joint angles were calculated using Cardan XYZ sequence of rotations (a sequence of plantarflexion/dorsiflexion, eversion/inversion, and abduction/adduction) with the distal segment expressed relative to the adjacent proximal segment. Throughout this study and based on previous studies (McClay & Manal, 1997; Pohl & Buckley, 2008; Pohl et al., 2007), rearfoot abduction/adduction was expressed as shank IR/ER because the rearfoot was considered fixed on the ground for the majority of stance. This method could accurately represent axial shank rotation.

After calculating the joint angles during the task, the data were time-normalized to the stance phase (102 data points). The stance phase was determined from the marker trajectory data of the calcaneus, second metatarsal head, and posterior superior iliac spine using Smith's custom-designed algorithm (Smith, Preece, Mason, & Bramah, 2015). Foot strike was defined as occurring at the point of maximum vertical displacement between the calcaneus and posterior superior iliac spine markers. Similarly, toe-off was defined as occurring at the point of maximum vertical displacement between the second metatarsal head and posterior superior iliac spine markers. This method could provide an accurate estimation of foot strike and toe-off. Foot strike angle was also calculated because differences in foot strike angles affect intra-foot kinematics and coupling of the foot joints (Pohl & Buckley, 2008). The foot strike angle was calculated as the angle between the vector calcaneus and second metatarsal head markers and anteroposterior axis according to the laboratory coordinate system. The angle of the foot during standing was subtracted from the foot strike angle. This calculation is strongly correlated with that of the traditional method, which involves the strike index using force plate data (Altman & Davis, 2012).

Coordination data of shank IR/ER and rearfoot EV/IN were calculated using a modified vector coding technique (Chang, Van Emmerik, & Hamill, 2008). An angle-angle diagram of shank IR/ER and rearfoot EV/IN (Fig. 1) was created and coupling angles (γ) were calculated as the angle regarding the horizontal line created by the vector connecting two consecutive time points (Eq.1).

$$\gamma_{j,i} = \tan^{-1}\left(\frac{y_{j,i+1} - y_{j,i}}{x_{j,i+1} - x_{j,i}}\right) \tag{1}$$

where 0Â° ≤ γ ≤ 360Â°, x_i, and $y_i$represent the proximal and distal joint angles, respectively. In addition, i represents the percent

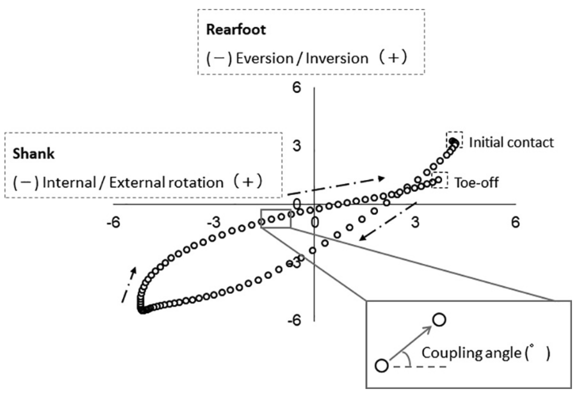

Fig. 1. Angle-angle diagram of shank internal rotation/external rotation and rearfoot eversion/inversion.

stance of the jth stride. Coordination variability was calculated as the circular SD of the coupling angle at each individual point of the gait cycle across five strides (Batschelet, 1981). This circular SD was averaged across the stance phase for each subject. All computations were performed in Scilab, version 6.0.0 (Enterprises, Versailles, France).

2.4. Statistical analysis

An independent t-test was used to determine gender-related differences in all spatiotemporal parameters and the foot strike angle. Effect sizes (ES) were also calculated using Cohen's d statistics. The ES were evaluated as follows: trivial (0–0.19); small (0.20–0.49); medium (0.50–0.79); and large (> 0.80). Statistical testing was performed using R version 3.3.2 (The R Foundation for Statistical Computing, Vienna, Austria).

We used a two-sample t-test of SPM to determine gender differences in coordination variability of the shank and rearfoot by statistically examining total coordination variability. SPM can tightly control the occurrence of type I errors, and the critical threshold was calculated based on a random field theory (Adler & Taylor, 2009). SPM procedures are conceptually identical to univariate procedures (e.g., univariate independent t-test), and the only apparent difference is that SPM uses a different probability distribution such as the random field theory (Pataky et al., 2013). If any values of SPM{T}exceeded the critical threshold, then the coordination variability at this point was considered significantly different between gender. Exact p-values were computed for each suprathreshold cluster using cluster size and random field theory distributions for SPM{T}topology. SPM{T}was calculated as follows (Eq. (2)) (Pataky et al., 2013):

$$T(q) = \frac{\bar{y}_B(q) - \bar{y}_A(q)}{\sqrt{\frac{1}{J}(s_A^2(q) + s_B^2(q))}} \quad (2)$$

where, q and J denote time points and responses (i.e. experimental recordings), respectively. $\bar{y}_A(q)$ and $\bar{y}_B(q)$ are the pointwise mean for the male and female trajectories, and $s_A(q)$ and $s_B(q)$ are the pointwise SD for the male and female trajectories. SPM analyses were implemented using the open-source SPM code (www.spm1d.org) in Matlab (R2018b; MathWorks Inc, Natick, MA, USA). Significance was set at $P < 0.05$ for comparisons.

3. Results

Speed (males: 2.2 (0.1) ms^{-1}, females: 2.0 (0.1) ms^{-1}, $P = 0.02$) and step length (males: 0.78 (0.04) m, females 0.71 (0.06) m, $P = 0.004$) significantly differed between genders, but there were no differences in cadence (males: 166.9 (7.6) steps/min, females: 172.7 (8.4) steps/min, $P = 0.11$). However, no differences in the normalized speed (males: 0.75 (0.04), females: 0.73 (0.04), $P = 0.11$, ES = 0.5 (medium)), normalized cadence (males: 48.9 (2.4), females: 49.4 (3.0), $P = 0.83$, ES = 0.19 (trivial)), normalized step length (males: 0.93 (0.05), females: 0.89 (0.07), $P = 0.17$, ES = 0.66 (medium)), and foot strike angle (males: 6.1 (2.3) degree, females: 4.9 (3.7) degree, $P = 0.41$, ES = 0.39 (small)) between males and females were found.

Coordination variability between shank and rearfoot considerably fluctuated in time series in both males and females (Fig. 2). Results of SPM are shown in Fig. 3. SPM found that there was no significant difference in coordination variability between gender during all individual points ($P > 0.05$). However, several t-values < -2 for the stances (38–39, 55–56 and 74–78%) tended to be close to the critical threshold compared with other individual points.

4. Discussion

This study aimed to investigate gender-related differences in coordination variability between shank and rearfoot during running using SPM. We hypothesized that differences in coordination variability between the shank and rearfoot for male and female participants during running can be detected. Contrary to our hypothesis, the SPM results showed no significant differences in coordination variability between genders.

Coordination variability has been suggested to be a critical index not only for the state of injury but also for the potential risk for

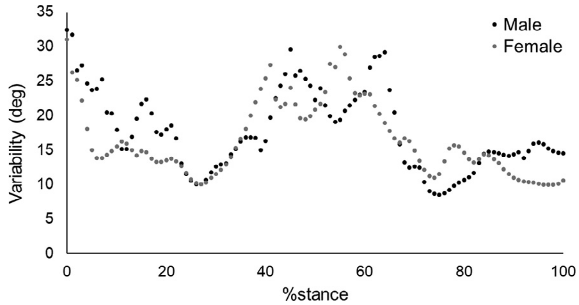

Fig. 2. Coordination variability between shank and rearfoot during running in males and females.

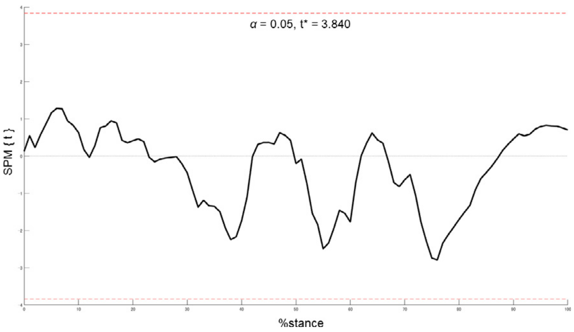

Fig. 3. Result of SPM in coordination variability during stance phase.

injury among individuals (Hamill et al., 2012). Numerous studies compared coordination variability between people with and those without running injury (e.g., PFP); however, few studies compared variability between healthy young males and females despite the fact that females have higher knee injury rates than males (Boling et al., 2010; Robinson & Nee, 2007). To our knowledge, only one study (Boyer et al., 2017) investigated gender differences in coordination variability between shank IR/ER and rearfoot EV/IN during running involving healthy young males and females. They reported no significant difference in coordination variability of shank and rearfoot kinematics between gender during running. However, another study (Boyer et al., 2017) averaged coordination variability for sub-phases such as early, mid, and late stances, and compared males and female runners. As shown in Fig. 2, coordination variability was volatile at the individual points, for example, variability in mid-stance in both males and females was approximately 10–30°. Thus, the difference in variability between the groups may be difficult to detect when gender difference of variability is averaged with the early, mid, and late stance data because the SD of the variability becomes large, such as that observed in the previous study (Boyer et al., 2017).

Therefore, if SPM was applied to individual coordination variability trajectory points, then we hypothesized that the difference in coordination variability between gender could be observed. However, SPM also found that there was no significant difference in coordination variability between gender at all individual points. We contend that the characteristics of the recruited participants may have helped to explain the findings of this study. Differences in injury rates have been reported to exist not only for gender (Boling et al., 2010; Robinson & Nee, 2007) but also for age (Taunton et al., 2002). Silvernail et al. (2015) investigated differences in coordination variability between the shank and foot during running in younger and older runners, but the variability did not differ between groups. They discussed that this was because the older people in their study were healthy, which potentially prevented injuries. Because this study also recruited healthy participants with no history of or current lower limb injuries, it was thought that SPM did not significantly differ for coordination variability between gender. Moreover, because the *t*-values of specific points such as 38–39, 38–39, 55–56, and 74–78% for stance tended to be close to the critical threshold, the results may be different with larger sample sizes. Further research of the influence of such factors on variability measurements is warranted.

Although SPM was originally developed to analyze brain function (Friston, Ashburner, Kiebel, Nichols, & Penny, 2007), it has been shown that it is generalizable to a variety of biomechanical data sets, such as joint kinematics (Nieuwenhuys, Papageorgiou, Desloovere, Molenaers, & De Laet, 2017), joint kinetics (Meyer et al., 2018), and electromyography (Robinson, Vanrenterghem, & Pataky, 2015). However, to our knowledge, SPM has not yet been performed to determine coordination variability between joints. The current study is the first to investigate the coordination variability between joints using SPM. We proposed that using SPM may provide new insight for analyzing coordination variability. In many studies, coordination variabilities were extracted as discrete parameters and compared between groups. For example, a recent study (Hafer et al., 2017) investigated coordination variability between the shank and rearfoot in those with and without iliotibial band syndrome and in uninjured and injured runners. That study did not find any difference in coordination variability between groups. However, coordination variability data were extracted before and after running fatigue, and those parameters may have been limited in temporal scope. Therefore, data regarding coordination variability trajectories were lost. If SPM is applied to individual points of variability, then different results might be obtained.

Our study has notable limitation. Coordination variability between shank IR/ER and rearfoot EV/IN was only analyzed because this study focused on the analysis of SPM. Coupling of shank IR/ER and rearfoot EV/IN may play a significant role in impact force attenuation during various tasks, and numerous studies (Ferber, Davis, & Williams, 2005; Kline & Williams, 2015; Pohl et al., 2007; Rodrigues, Chang, TenBroek, van Emmerik, & Hamill, 2015; Sinclair & Taylor, 2014; Tiberio, 1987) have investigated such coupling. However, coupling between the thigh and shank is also involved in absorption impact during running (Silvernail et al., 2015). Thus, variability of other coupling, such as between the thigh and shank, may differ between males and females when using SPM. These limitations should be addressed in future studies.

5. Conclusion

SPM showed no significant differences in coordination variability between genders. This study demonstrated that coordination variability between the shank and rearfoot during running may not be associated with the differences in the incidence rates of knee injuries of male and female participants. However, SPM may provide new insight into analyzing coordination variability in the future.

Conflict of interest

The authors declare no conflict of interest.

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