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Forefoot–rearfoot coupling patterns and tibial internal rotation during stance phase of barefoot versus shod running

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Abstract

Background. Based on twisted plate and mitered hinge models of the foot and ankle, forefoot–rearfoot coupling motion patterns can contribute to the amount of tibial rotation. The present study determined the differences of forefoot–rearfoot coupling patterns as well as excessive excursion of tibial internal rotation in shod versus barefoot conditions during running.

Methods. Sixteen male subjects ran 10 times at 170 steps per minute under the barefoot and shod conditions. Forefoot–rearfoot coupling motions were assessed by measuring mean relative phase angle during five intervals of stance phase for the main effect of five time intervals and two conditions (ANOVA, $P < 0.05$). Tibial internal rotation excursion was compared between the shod and barefoot conditions over the first 50% of stance phase using paired *t*-test, ($P < 0.05$).

Findings. Forefoot adduction/abduction and rearfoot eversion/inversion coupling motion patterns were significantly different between the conditions and among the intervals ($P < 0.05$; effect size = 0.47). The mean absolute relative angle was significantly modified to 37° in-phase relationship at the heel-strike of running with shoe wears. No significant differences were noted in the tibial internal rotation excursion between shod and barefoot conditions.

Interpretation. Significant variations in the forefoot adduction/abduction and rearfoot eversion/inversion coupling patterns could have little effect on the amount of tibial internal rotation excursion. Yet it remains to be determined whether changes in the frontal plane forefoot–rearfoot coupling patterns influence the tibia kinematics for different shoe wears or foot orthotic interventions. The findings question the rational for the prophylactic use of forefoot posting in foot orthoses.

Keywords: Forefoot; Rearfoot; Relative phase angle; Tibia internal rotation

1. Introduction

Excessive tibial internal rotation coupling with rearfoot eversion during the first half stance phase of running was associated with patella-femoral pain syndrome, Achilles tendon pain and shin splint (Clement et al., 1981; Smart et al., 1980; Tiberio, 1987; Viitasalo and Kvist, 1983). The amount of internal tibial rotation is proposed to be related to coupling motion patterns between the forefoot and rearfoot (Lundberg, 1989; Naster et al., 2002). A twisted plate model of the foot suggests that the forefoot produces counter motions with respect to the rearfoot segments during barefoot running (Hunt et al., 2001; Sarrafian, 1993). From heel-strike through footflat, the rearfoot is everted and the forefoot becomes flexible to

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absorb shock and adapt itself to irregularities in the ground floor surface (Nordin and Frankle, 2001). A cross-correlation between the rearfoot and forefoot motion indicated that rearfoot eversion/inversion was highly correlated to forefoot plantar/dorsiflexion ($r < -0.85$) and abduction/adduction ($r > 0.94$) with no phase shift during the stance phase of barefoot running (Pohl et al., 2006). Johanson et al. (1994) reported that a large forefoot inversion with respect to the rearfoot results in an abnormal gait pattern when resulting in compensatory subtalar joint pronation. Furthermore, using a mitered hinge model, rearfoot eversion in the frontal plane was found to be coupled with tibial internal rotation during gait (Pohl et al., 2006; Nigg et al., 1993). A high correlation value ($r = 0.99$) was reported between rearfoot eversion and tibial internal rotation during the first 50% stance phase of gait (Pohl et al., 2006; Nigg et al., 1993). Therefore, based on the twisted plate and mitered hinge models, the forefoot and rearfoot coupling motion patterns could contribute to the amount of tibial rotation.

In previous studies the rearfoot and tibia coupling motion was modelled as a single rigid segment because of technical difficulties associated with evaluating the forefoot motion in a shoe condition. Furthermore, in vivo studies on the forefoot motions, subjects were tested in barefoot condition to enable tracking of markers on the forefoot (Pohl et al., 2006; Hunt et al., 2001). Therefore, footwear effects on the three-dimensional forefoot motion coupling with the rearfoot frontal plane motion and their contributions to the tibial rotation remained unknown.

The use of forefoot posting in orthotic interventions to compensate excessive foot pronation is still misunderstood. Clinically, it is believed that abnormal foot pronation is associated with forefoot excessive motions with respect to the rearfoot (Johanson et al., 1994; Tillman et al., 2003). However, Johanson et al. (1994) indicated that posting in the rearfoot was more effective in controlling foot pronation than posting in the forefoot, even in the presence of a forefoot deformity. A better understanding of the forefoot and rearfoot coupling relationships and their contributions to the tibial rotation in asymptomatic feet will provide information of the importance of forefoot posting in the orthotic interventions in controlling excessive tibial rotation.

A number of techniques have been used to examine coupling motion relationships between rearfoot and tibia during dynamic motions. Cross-correlations are based on the assumption that linear relationships exist between two adjacent segments. However, this technique is not useful in determining the degree of linkage between the segments that have a non-linear relationship (Sideway et al., 1995). Rearfoot eversion and tibial internal rotation (EV/TIR) excursion ratio is used to provide a measure of the relative motion between the rearfoot and tibia from heel-strike to the respective peaks around midstance (DeLeo et al., 2004). In the recent studies, the EV/TIR ratio varied between 0.65 in the normal shod (Stacoff et al., 2000) and 2.40 in the barefoot conditions (Pohl et al., 2006). These values suggest that the rearfoot is everted by 1° for every 1.54° and 0.41° tibial internal rotation in shod and barefoot conditions, respectively. In the present study, EV/TIR excursion ratio will be used to determine if the tibia has a relatively greater motion with respect to the rearfoot (Nawoczenski et al., 1995; Nigg et al., 1993; Williams et al., 2001). For example, runners with lower EV/TIR ratios display relatively more tibial internal rotation with respect to the rearfoot eversion rotation and increasing the risk for knee related injuries (McClay and Manal, 1997; Williams et al., 2001). A continuous relative phase angle technique (CRP) was also proposed to describe the coupling motion relationships of two adjacent segments throughout the stance phase (Hamill et al., 1999). This technique indicates the amount of in-phase or out-of-phase relationships between two adjacent segments. Hamill et al. (1999) reported that the relationship between the rearfoot and tibia was more out-of-phase in the strike phase than the rest of stance in a group of healthy runners. However, there is no information regarding to coupling motion patterns of the forefoot and rearfoot during shod running in the literature. Thus, relative phase angle technique will be used to provide quantitative information on the forefoot–rearfoot coupling motion patterns throughout the stance phase of barefoot running versus running with sandals.

With respect to the following three assumptions, sandals were used as footwears in the present study. Firstly, the sandals' adjustable straps and the bottom midsole designs enable greater changes in the forefoot and rearfoot coupling motion patterns than running shoe. Secondly, the sandal allows tracking of the rearfoot and forefoot surface markers during running trials. Finally, sandals are often used to evaluate the effects of foot orthoses on the rearfoot and tibia coupling motions (Branthwaite et al., 2004; Nawoczenski et al., 1995). However, the confounding effects of the sandal on the outcome measures of these coupling motions were unknown in the literature.

In current study, we hypothesized that tibial internal rotation is increased when the forefoot–rearfoot coupling patterns are modified to a more in-phase relationship with shoe wears during the stance phase of running. The purposes were: (i) to compare the excursion of tibial internal rotation and rearfoot eversion from heel-strike to peak value during the stance phase of running in barefoot versus shod conditions, (ii) to determine differences in mean relative phase angle of the forefoot eversion/inversion and rearfoot eversion/inversion ($FF_{ev/in}$–$RF_{ev/in}$), forefoot dorsi/plantarflexion and rearfoot eversion/inversion ($FF_{d/p}$–$RF_{ev/in}$), forefoot adduction/abduction and rearfoot eversion/inversion ($FF_{ad/ab}$–$RF_{ev/in}$) during the stance phase of barefoot versus shod running.

2. Methods

Sixteen able-bodied healthy men having an average age of 28.2 (SD 5.2 years), weight of 82.3 (SD 10.4 kg) and