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Original article

The effects of forefoot varus on hip and knee kinematics during single-leg squat☆

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ABSTRACT

Foot misalignments, such as forefoot varus (FV), have been associated with musculoskeletal injuries in the proximal joints of the lower limb. Previous theories suggested that this association occurs because FV influences knee and hip kinematics during closed kinetic chain activities. However, research on the effects of FV in the kinematics of the lower limb is very scarce. Therefore, the purpose of this study was to compare the knee and hip kinematics between subjects with and without FV during a functional weight-bearing activity. Forty-six healthy adolescents were divided into two groups: group of subjects with FV (VG, $n = 23$) and group of subjects with aligned forefoot (CG, $n = 23$). A kinematic evaluation was conducted while the subjects performed a single-leg squat task. The variables of interest were hip internal rotation and adduction and knee abduction excursions at 15°, 30°, 45° and 60° of knee flexion. Between-group comparisons were performed with multivariate analysis of variance. Results showed that the VG presented greater hip internal rotation when compared with the CG across all evaluated knee flexion angles ($P = 0.02–0.0001$). No differences between groups were observed in hip adduction or knee abduction ($P > 0.05$). These results indicate that FV influences the transverse plane hip movement patterns during a functional weight-bearing activity. Considering that excessive hip internal rotation has been associated with knee injuries, these findings might contribute for a better understanding of the link between FV and injuries of the proximal joints of the lower limb.

1. Introduction

Alterations in the foot mechanics during weight-bearing activities may affect the movement patterns of proximal joints, predisposing to the occurrence of overload injuries (Fonseca et al., 2007). Forefoot varus (FV) is a foot misalignment in which the plane of the metatarsal heads is supinated in relation to the rearfoot when the subtalar joint is fixed in a neutral position (Root et al., 1977). It is believed that FV increases the pronation of the subtalar joint (subtalar hyperpronation) during foot stance, to allow the medial metatarsals to contact the floor (Alonso-Vázquez et al., 2009). Therefore, this forefoot misalignment may produce significant compensations in other body segments and may have important clinical relevance, especially considering that an association has been observed between FV and injuries in the knee (Lun et al., 2004), hip (Gross et al., 2007), and lumbar spine (Rothbart et al., 1995).

Subtalar joint pronation is a triplanar motion composed of calcaneus eversion and talus plantar flexion and internal rotation. Because the talus is firmly stabilized by the ankle mortise, subtalar joint pronation is necessarily associated with tibial internal rotation in closed kinetic chain (Rockar, 1995). Therefore, excessive subtalar joint pronation is believed to result in increased lower limb internal rotation during weight-bearing activities (Tiberio, 1987). Also, it has been proposed that a greater calcaneal eversion, associated with subtalar hyperpronation, could result in increased knee abduction in closed kinetic chain activities (Gross, 1995). It has been theorized that these proximal compensations, associated with foot misalignments, could significantly influence patellofemoral joint mechanics and contribute to the development of patellofemoral pain (PFP) (Tiberio, 1987; Powers, 2003). Supporting these theories, prospective studies have demonstrated that FV and subtalar hyperpronation are risk factors for the development of PFP (Lun et al., 2004; Boling et al., 2009). However, very few studies have

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attempted to verify whether FV and subtalar hyperpronation are, in fact, associated with altered movement patterns in the knee and hip joints.

There is some evidence confirming an association between foot misalignments and altered movement patterns in the lower limbs. Previous studies have demonstrated that inducing subtalar hyperpronation in subjects with aligned feet indeed produces kinematic alterations in the tibia and femur in gait (Lafortune et al., 1994; Souza et al., 2009). However, these studies have verified the acute effects of inducing foot misalignments in subjects with aligned feet. To our knowledge, the only studies that have included lower limb kinematic evaluations of subjects who actually present FV, were conducted with children (Alonso-Vázquez et al., 2009) or restricted the evaluation to the knee joint (Bittencourt et al., 2012). Therefore, the effects of this forefoot misalignment in the movement patterns of other segments, such as the hip joint, in subjects other than children, are still unknown.

Lastly, previous studies that have attempted to verify the influence of foot misalignments on lower limb biomechanics have included kinematic evaluations during gait (Lafortune et al., 1994; Alonso-Vázquez et al., 2009; Souza et al., 2009). However, research on the effects of FV on lower limb kinematics during other functional activities, such as the single-leg squat, is still scarce (Bittencourt et al., 2012). The identification of altered movement patterns in subjects with FV could provide better justification for the use of foot orthosis as an intervention for rehabilitation and prevention of injuries. Therefore, the purpose of this study was to compare the hip and knee kinematics between adolescents with and without FV during a single-leg squat task. It was hypothesized that subjects with FV would present greater hip internal rotation and greater knee abduction when compared with subjects with aligned forefoot.

2. Methods

2.1. Subjects

Forty-six healthy asymptomatic subjects, 14–18 years of age, volunteered for this study and were divided into two groups: group of subjects with compensated forefoot varus (VG, $n = 23$, 11 male, 12 female) and group of subjects with neutral forefoot alignment (CG, $n = 23$, 11 male, 12 female). The presence of compensated forefoot varus was established if the subject presented an angle of forefoot varus $\geq 8°$ and a weight-bearing rearfoot eversion angle $\geq 10°$ (Buchanan and Davis, 2005). The decision of including the rearfoot angle as an additional inclusion criterion was made to ensure that the included subjects presented subtalar hyperpronation. It would be unlikely that FV would influence the proximal segments of the kinetic chain if no compensatory subtalar hyperpronation were occurring (Hlavac, 1970; Tiberio, 1988).

Calculations regarding sample size were conducted *a priori* using the Statistica software (StatSoft Inc, Tulsa, USA). Hip internal rotation excursion was considered the primary outcome. The calculations were made using $\alpha = .05$, $\beta = .20$, an expected difference between groups of 4.3°, and a within-group standard deviation of 5.0°. These parameters were based on the findings of previous research (Nakagawa et al., 2012). Based on these parameters, 23 subjects per group were required to adequately power the study for this variable of interest.

Adolescents were recruited considering that subjects in this life stage present a very high prevalence of knee dysfunctions, and these dysfunctions have been related to foot misalignments (Mølgaard et al., 2011). The following exclusion criteria were established for this study: 1) injury to either lower extremity in the previous 6 months; 2) history of congenital deformity or surgery in the lower extremities; 3) regular practice of physical activity, in a frequency of 3 times per week or greater; 4) presence of valgus forefoot; 5) presence of neurological or systemic conditions that could impair the participant's ability to perform the proposed evaluations. The subjects were recruited from local high-schools and were invited to participate in the study, which was approved by the Ethics Committee of the University. Each volunteer signed an informed consent form. Parental or guardian consent was also obtained for the volunteers younger than 18 years of age.

2.2. Procedures

Research on the effects of FV on lower limb biomechanics has increased in the last few decades. In that context, several traditional and innovative ways for evaluating forefoot alignment have been utilized and include evaluations using laser technology (Chen et al., 2003), camera systems (Gross et al., 2007; Monaghan et al., 2013) and clinical evaluations using a standard goniometer (Root et al., 1979). In the current study, a standard goniometric evaluation was chosen due to the fact that this evaluation can more easily be performed in the clinical setting. Also, previous studies have already demonstrated that greater values of FV, identified by this goniometric evaluation, are associated with other measurements for identifying subtalar hyperpronation, such as the rearfoot eversion test (Buchanan and Davis, 2005; Johanson et al., 2010; Scattone Silva et al., in press), the navicular drop test (Buchanan and Davis, 2005; Scattone Silva et al., in press) and the Foot Posture Index (Scattone Silva et al., in press).

For this forefoot alignment evaluation, the subjects were positioned in prone lying, with the hip of the evaluated limb in a neutral position and the knee extended. The other lower limb was positioned in hip abduction and external rotation, with 90° of knee flexion. In this position, lines were drawn bisecting the lower third of the leg and the calcaneus (Buchanan and Davis, 2005). The subtalar joint was held in a neutral position for the forefoot alignment measurement, as previously performed by Elveru et al. (1988). A universal goniometer was used for measuring forefoot alignment. One hand of the examiner held the subject's subtalar joint in its neutral position, and the other hand was used to align the goniometer so that the fixed arm was positioned perpendicular to the bisection of the calcaneus, and the moveable arm was aligned with an imaginary line drawn through the metatarsal heads (Buchanan and Davis, 2005). Both lower limbs were evaluated in a random order.

Then, the subject was positioned standing on a 45.0 cm-high step that was positioned close to a wall, for the assessment of the rearfoot angle. The rearfoot angle was assessed with a universal goniometer with the subject in a single-leg relaxed stance. The subject was instructed to flex the opposite knee and was allowed to touch the wall with both hands for balance, if necessary. The angle between the bisection of the lower third of the leg and the bisection of the calcaneus was recorded (Buchanan and Davis, 2005). Three measurements of the forefoot and rearfoot alignments were taken and average values were calculated for analysis. For greater reliability, the same examiner performed all foot alignment assessments.

A previous study, using the same methodology, tested the reliability of these measurements of foot alignment in 15 healthy adolescents. In this study, the intraclass correlation coefficients ($ICC_{3,3}$) and the standard error of measurement of the forefoot varus angle and the rearfoot angle measurements were 0.99 (0.55°) and 0.94 (0.89°), respectively (Scattone Silva et al., 2013), indicating that these measurements are reliable.

Next, for the subjects in the VG, the lower limb presenting FV was submitted to a kinematic evaluation. For subjects with bilateral