The Effect of Walking Speed on Foot Kinematics is Modified When Increased Pronation is Induced

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Background: The relation between walking speed and foot kinematics during gait is not well established, and neither is it clear whether this relation is modified in the presence of factors expected to increase pronation (eg, abnormal foot alignment). Understanding how foot kinematics is affected by walking speed under varying conditions could contribute to our understanding of stresses to the musculoskeletal system during walking. We evaluated the effect of walking speed on foot kinematics in the frontal plane during gait and determined whether this effect is modified by using medially inclined insoles that force the foot into increased pronation.

Methods: Twenty-six healthy young adults were assessed while walking on a treadmill wearing flat insoles and wearing medially inclined insoles. Foot kinematics in the frontal plane was measured with a three-dimensional motion analysis system. Data were analyzed during the stance phase of gait.

Results: There was no main effect of speed on average calcaneal position. However, there was a significant insole type × walking speed interaction effect. In the flat insole condition, increased walking speed was associated with a less inverted average calcaneal position (or greater magnitudes of eversion), whereas in the inclined insole condition, higher speeds were associated with a less everted average calcaneal position (or increased magnitudes of inversion).

Conclusions: The magnitude of foot eversion increases at faster gait speeds under typical conditions. In the presence of factors that induce excessive pronation, however, this effect is reversed. Results suggest that individuals use greater active control of foot motion at faster speeds in the presence of excessive pronation to improve push-off efficiency. Potential clinical consequences of this functional strategy are discussed. (J Am Podiatr Med Assoc 106(6): 419-426, 2016)

Excessive foot pronation during walking is a potential risk factor for several musculoskeletal abnormalities,[1] such as shin splints,[2] plantar fasciitis,[3] patellofemoral pain syndrome,[4] and low back pain.[5] The speed of walking might affect the magnitude of foot pronation and, therefore, increase the stresses in the musculoskeletal system of excessive pronators.[6] However, the relation between walking speed and foot pronation is not well established. In addition, it is not clear whether this relation is modified in the presence of factors that increase foot pronation.

Foot pronation during the stance phase of gait is partly explained by the interaction between the foot and the ground reaction force generated during the initial contact of the foot. This force is applied laterally to the subtalar joint axis, creating an external eversion moment at the ankle-foot complex, typically lasting from loading response to midstance. During this part of the stance phase, the eversion moment generates calcaneal eversion, which is the component of pronation in the frontal plane.[7] The magnitude of pronation observed,

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however, seems to depend on a variety of biomechanical factors that modify how the foot will respond to the ground reaction force. For example, in the presence of varus deformity of the foot[8-11] or hypermobility of the first ray,[12] a greater magnitude of pronation is observed. Nonlocal factors, such as femoral anteversion and reduced passive mechanical resistance provided by the hip external rotator muscles, may increase hip and lower-limb internal rotation, which, owing to intersegmental coupling, favors increases in the magnitude of pronation as well.[9,13]

At fast walking speeds, because of the increase in the magnitude of ground reaction forces, a greater magnitude of foot pronation is expected.[6] If that is the case, the presence of biomechanical factors that increase foot pronation might be particularly problematic for individuals whose activities involve walking at faster speeds. Understanding the effect of gait velocity on the magnitude of pronation might contribute, therefore, to our understanding of stresses applied to the musculoskeletal system during walking. The aim of this study was to evaluate the effect of walking speed on foot kinematics in the frontal plane during gait and to verify whether this effect is modified when excessive pronation is induced with the use of medially inclined insoles.

Methods

Participants

Twenty-six healthy young adults (8 men and 18 women) from the institution community volunteered to participate in this study. The participants had no history of lower-limb pain or injury in the past 12 months and no history of lower-limb orthopedic surgery. To minimize the chances of including in the study individuals with excessive pronation, we included only those volunteers with tibia-forefoot alignment within the reference range (ie, $\leq 24°$).[14] Tibia-forefoot alignment was measured following a standard procedure described in detail by Mendonça et al[14] and Souza et al.[9]

In addition, to guarantee that deficits in range of motion would not prevent excessive pronation induced in the experiment, we included only volunteers who had at least 10° of passive eversion range of motion, 13° of passive dorsiflexion range of motion at the ankle,[15] and 23° of passive internal rotation range of motion at the hip.[16] Participants who felt pain or discomfort during the evaluation were excluded from the experiment.[9] A trained physical therapist (J.F.H.) performed all of the tibia-forefoot alignment measurements and range-of-motion data assessments. Her reliability for the procedures was assessed and obtained intraclass correlation coefficients (ICCs) [3,3] greater than 0.80.

Six participants presented excessive pronation in the flat insole condition despite having foot alignment within the reference range. Data from a study that evaluated foot pronation (eversion of the rearfoot relative to the shank) of typical young adults with similar methods and under similar task conditions (walking on a treadmill) directed the criteria to identify excessive pronators.[9] The mean $\pm$ SD eversion observed in this study was $4.59° \pm 2.11°$. Therefore, individuals who presented mean rearfoot eversion relative to the shank during walking greater than 6.7° (mean $\pm$ 1 SD) were excluded from the present study. This procedure allowed us to create a control condition in which individuals walked without excessive pronation to evaluate the effect of gait speed in the typical situation. Therefore, 20 individuals (6 men and 14 women) remained in this study after applying the exclusion criteria. Their mean $\pm$ SD age, height, and weight were 23.7 $\pm$ 3.4 years, 1.68 $\pm$ 0.06 m, and 64.2 $\pm$ 12.1 kg, respectively, and their descriptive data are presented in Table 1.

Instrumentation

A three-dimensional motion analysis system (Codamotion; Charnwood Dynamics Ltd, Rothley, England) with three cameras tracked the motion of the foot and shank during walking at a sampling rate of 100 Hz.[17] The examiner used a pointer integrated with the motion analysis system to identify virtual (anatomical) markers that were used to create a coordinate system for each segment. Proximal markers on the lateral and medial epicondyles of the femur and distal markers on the lateral and medial malleoli defined the shank. Proximal markers on the medial and lateral malleoli and distal markers on the sustentaculum tali and peroneal tubercle defined the rearfoot.[18] The examiner attached clusters containing three tracking markers each to the participants' shank and calcaneus of the right lower limb (Fig. 1).[19,20] The shank cluster was rigid and was attached to the posterior aspect of the distal half of the segment with double-sided tape and Velcro brand hook and loop fasteners (Velcro USA Inc, Manchester, New Hampshire). The calcaneal cluster was rigid, involved the calcaneus posteriorly, and was attached with double-sided

Table 1. Descriptive Data for the 20 Study Participants

Descriptive Data	Right	Left
Tibia-forefoot alignment (°)	12.8 ± 4.5	14.2 ± 6.7
Range of motion (°)		
Hip internal rotation	38.4 ± 10.8	40 ± 9.6
Ankle eversion	17.2 ± 3.9	17.6 ± 3.8
Ankle dorsiflexion	17.9 ± 4.8	18.1 ± 4.2

Note: Data are given as mean ± SD.

tape and Nexcare Micropore tape (3M, St. Paul, Minnesota). Finally, identification of heel contact and toe-off events was based on the motion of two technical markers attached to the shoe.[21]

The participants walked on an electric treadmill (ProAction G635 Explorer; BH Fitness, Vitoria-Gasteiz, Spain) with no inclination. All of the volunteers used the same model of shoes. Multiple shoe sizes were available to guarantee optimal fit. The shoes had a posterior opening to allow direct placement of the cluster on the calcaneus. Each participant walked on the treadmill under two different conditions defined by the type of shoe insole. For the flat insole condition, participants wore a pair of noninclined (flat) insoles (Fig. 2A). A pair of 15° medially inclined insoles was used to induce increases in foot pronation (inclined insole condition). This inclination was applied throughout the entire length of the insole (Fig. 2B). Both insoles were made of high-density ethyl vinyl acetate in ten different shoe sizes. The insoles were inserted into a neutral shoe (Crusader 4; Mizuno Inc, Ho Chi Minh City, Vietnam).

Procedure

The Reasearch Ethics Committee of the Federal University of Minas Gerais approved the present study, and all of the participants signed an informed consent form before data collection. Initially, a designated examiner (a physical therapist) attached the clusters of tracking markers to the participant's shank and calcaneus. After that, the participant stood on the treadmill wearing shoes with flat insoles bilaterally. A well-trained examiner created the virtual markers on the specific anatomical references described previously. The examiner then placed the right subtalar joint in the neutral position following the standard procedure previously described by Sell et al.[22] The volunteers maintained that position for 5 sec while the movement analysis system registered it. The procedure was repeated three times. This static



Figure 1. Clusters with tracking marks attached to the shank and calcaneus.

trial provided the necessary data to 1) create the coordinate systems of the shank and calcaneus, assumed to be rigid bodies (ie, movements between shank bones and between calcaneal bones were not modeled),[23,24] and 2) define the neutral (0°) position of the calcaneus relative to the shank in the frontal plane.

After the static trial, participants walked on the treadmill at two different speeds (2 and 5 km/h) using either flat insoles or medially inclined insoles designed to increase foot pronation. The latter was used to induce an increase in the magnitude of pronation during gait. For each of the four experimental conditions (two walking speeds and two types of insoles), participants walked for 30



Figure 2. A, Flat insoles. B, Inclined insoles.

complete cycles. The gait cycle was defined by two consecutive heel strikes of the reference foot. Before data collection at each condition, participants practiced walking on the treadmill until they felt comfortable with the task. The test conditions were performed in succession, and their order was randomized by raffle.

Data Reduction

Data were processed with motion analysis software (Visual3D; C-Motion Inc, Rockville, Maryland). Laboratory and body segment coordinate systems (orthogonal x-, y-, and z-axes)[9,18] were created in which the x-axis is the posteroanterior axis, the y-axis is the lateromedial axis, and the z-axis is the axial axis. The shank and calcaneal clusters of tracking markers were associated with each corresponding coordinate system. Position data from the tracking markers were smoothed using a second-order, zero-lag, Butterworth low-pass filter with a cutoff frequency of 6 Hz.[25]

We computed calcaneal inversion-eversion with respect to the shank (around their x-axes) during the stance phase of gait to infer about supination-pronation under the four experimental conditions. Rearfoot angular position was computed based on the Cardan flexion/extension, inversion/eversion, internal/external rotation sequence.[24] Negative position values reflected everted (pronated) positions, whereas positive position values indicated inverted (supinated) positions. Neutral position (0°) of the calcaneus with respect to the shank refers to the neutral subtalar position registered in the static trial. For each test condition, the mean calcaneus eversion-inversion angular position was computed using data from the 30 stance phases registered. That is, analyses were based on the average calcaneal position of the time-series corresponding to each condition during the stance phase. The stance phase was defined to be the period between two gait events: initial contact and toe-off. We used the procedures described in the study by Ghoussayni et al[21] to identify these events.

Reliability

We conducted a pilot study with ten individuals using the methods described to evaluate the intertest reliability of calcaneal eversion-inversion measurement. Data were collected in two different sessions, separated by 1 week. The coefficient of multiple correlations was used to verify the reliability of the calcaneal eversion-inversion curves between the two assessment sections.[26] The mean ± SD coefficient of multiple correlations was 0.81 ± 0.13, which indicates good reliability.[27] We also estimated the intra-examiner reliability for determining the neutral position of the subtalar joint on the static trial. The $ICC_{3,3}$ obtained was 0.81. None of the volunteers who participated in the pilot study were participants in the main study.

Statistical Analysis

Two-way repeated-measures analysis of variance was used to evaluate the effect of insole type (flat and inclined) and walking speed (2 and 5 km/h) on the average calcaneal position during the stance phase of gait. The alpha level for the analysis was established at 0.05.

Results

The main effect of insole type was significant ($F_{1,19} = 128.58$; $F_{\text{critical}} = 4.38$; $P = .001$; $\eta = 0.871$). Use of the inclined insole caused a mean increase in calcaneal eversion of 6.61°, suggesting that the strategy to increase pronation was effective. Mean ± SD calcaneal inversion-eversion values in all four test conditions are presented in Table 2. Therefore, this experimental manipulation was effective in increasing pronation. There was no main effect of speed on average calcaneal position ($F_{1,19} = 0.11$; $F_{\text{critical}} = 4.38$; $P = .742$; $\eta = 0.006$). There was a significant insole type × walking speed interaction effect ($F_{1,19} = 7.33$; $F_{\text{critical}} = 4.38$; $P = .01$; $\eta = 0.278$). Figure 3 shows that the type of insole modified the direction of effect of gait speed on average calcaneal position. In the flat insole condition, an increase in gait speed from 2 to 5 km/h caused a mean ± SD increase in calcaneal eversion of 0.51° ± 1.75°. When excessive pronation was induced by the inclined insole, the increase in gait speed led to a mean ± SD decrease in calcaneal eversion of 0.31° ± 1.22°. To confirm that the interaction effect was driven by a systematic difference in the effect of speed on foot motion, a post hoc t test was conducted. The t test verified that the change in the average inversion-eversion position between speed conditions using flat insoles was, indeed, different (and opposite in sign) from the change in this variable when inclined insoles were used ($t_{19} = 2.71$; $t_{\text{critical}} = 2.09$; $P = .014$). Figure 4 presents calcaneal inversion-eversion curves for the flat and inclined insole conditions at two different walking speeds during the stance phase of gait.

Table 2. Calcaneal Inversion-Eversion During the Stance Phase

Walking Speeds	Flat Insole Condition	Inclined Insole Condition
Slower (2 km/h)	1.334° ± 4.292°	–5.682° ± 4.866°
Faster (5 km/h)	0.825° ± 3.831°	–5.374° ± 5.138°

Note: Data are given as mean ± SD. Negative values represent eversion and positive values represent inversion.

Discussion

The objectives of the present study were to investigate the effect of gait speed on the magnitude of foot pronation during the stance phase of gait and to verify whether such an effect would be modified in the presence of factors that increase pronation. We hypothesized that the magnitude of pronation would increase as a function of gait speed because greater magnitudes of ground reaction forces are expected when individuals walk faster. We also hypothesized that gait speed would produce larger increases in the magnitude of pronation in the presence of factors that lead to excessive pronation. To test these hypotheses, we asked individuals to walk on a treadmill and computed the average angular position of the calcaneus with respect to the shank (in the frontal plane) to infer about foot pronation. Individuals walked at two different speeds using either flat or medially inclined insoles. All of the participants showed significant increases in the mean magnitude of pronation when wearing the inclined insoles. In line with the hypothesis, the magnitude of pronation increased with walking speed under the flat insole condition. Contrary to the hypothesis, however, the effect of walking speed was reversed when using the inclined insoles. The mean magnitude of pronation reduced as walking speed increased.

The observed reduction in the mean magnitude of pronation could be related to the pattern of muscular forces generated by the plantar flexors at faster speeds. There is evidence that increases in gait speed are related to increases in power generation of this muscle group.[28,29] Considering that most plantar flexor muscles are also supinators,[30] an increase in the action of this muscle group, required for faster walking speeds, could lead to reduced magnitudes of pronation as a by-product. This explanation, though reasonable, is weakened by the fact that a reduction in the mean magnitude of pronation was observed only when excessive pronation was induced by the inclined insoles. When excessive pronation was not induced

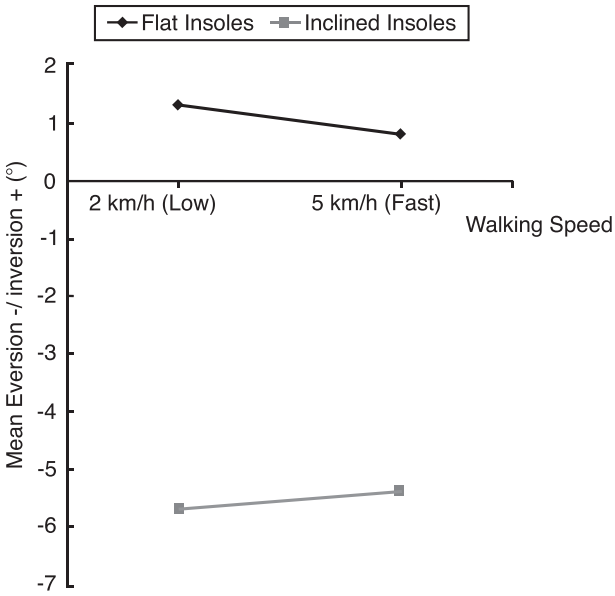


Figure 3. Mean calcaneal position in the frontal plane during the stance phase of gait for each study condition: walking speed (2 and 5 km/h) and insole type (flat and inclined).

by the inclined insole (flat insole condition), the magnitude of pronation increased as gait speed increased. Given that the magnitude of ground reaction force is expected to increase as walking speed increases,[31] a reduction in mean pronation magnitude in the incline insole condition does imply

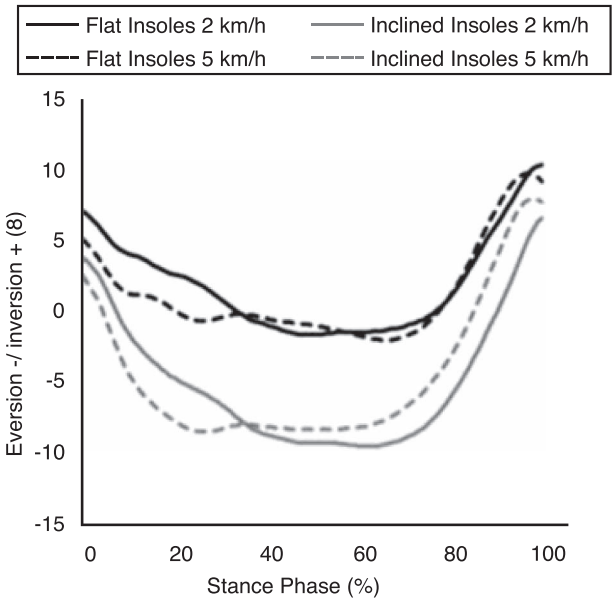


Figure 4. Calcaneal inversion-eversion during the stance phase of gait (mean curve defined over the 30 gait cycles of all of the participants).

some form of active control mechanism. The key to explaining the present results, however, is to identify a mechanism that 1) could override the effect of the external eversor moment (generated by the ground reaction force) on foot motion at faster speeds and 2) would come into play only in the presence of factors that increase foot pronation.

The basis for explaining the results might be the detrimental effects of pronation for generation of force during terminal stance and push-off. When the foot is pronated, the midtarsal joint is unlocked, giving flexibility to the foot.[32] Although such flexibility is optimal for absorbing impact during the early portions of the stance phase of gait,[33,34] it is detrimental for efficient propulsion at later phases because excessive movement and tissue deformation in the foot could dissipate part of the force produced by plantar flexor muscles.[34] An efficient plantar flexor moment to propel the leg and body forward requires a foot that behaves as a rigid lever, which in practice means a supinated foot.[32,35] It can be expected that prolonged pronation would be particularly problematic for faster walking speeds given the greater demand for generation of muscular power. As a result, when inclined insoles were used, participants may have used muscular strategies to control pronation in an attempt to improve efficiency at push-off when required to walk faster. This control could be obtained locally through activation of the supinator muscles.

The trajectories of the foot under the different experimental conditions displayed in Figure 4 supports this explanation. These trajectories suggest that the reversed effect of gait speed on average calcaneal position under the inclined insole condition was primarily driven by foot kinematics at later portions of the stance phase of gait. During early stance, the magnitude of pronation seems to be greater at the faster speed for both insole conditions. It is only during mid- and late stance that this effect is reversed for the inclined insoles condition (the magnitude of pronation decreases at faster speeds). The fact that possible active control mechanisms came into play only at these later portions of the stance phase reinforces the idea that individuals were attempting to minimize the detrimental effects of excessive pronation at faster speeds, conditions in which the demand for power generation is higher.

With flat insoles, during push-off, the foot was no longer pronated (mobility of the midtarsal joint was reduced) and, thus, was optimally stable for propulsion of the body.[11,32] Therefore, no active control mechanism was required to increase propulsion and control the increase in pronation associated with increased speed. The increase in the magnitude of pronation happened at an instant in the cycle that did not interfere with the muscular action at push-off. Future studies could assess this hypothesis by evaluating whether muscular activity of supinator muscles is in fact increased when excessive pronation is induced by inclined insoles at faster speeds.

The inclined insoles in the present study stood proxy for biomechanical factors that have been associated with excessive pronation (eg, altered foot bone alignment, low hip stiffness).[36] The results, therefore, could have implications for understanding the nature of stresses arriving at the musculoskeletal system of excessive pronators as the speed of gait varies. Such understanding might shed light on the mechanisms underlying the development of pathologic conditions in excessive pronators who use walking as a physical activity (typically involving higher speeds). Although actively controlling foot pronation may have the positive effect of optimizing propulsion and help in speeding up, it may be at the cost of overstressing muscle-tendon tissues. For example, the tibialis posterior and soleus muscles are ankle invertors and can eccentrically control foot pronation.[30] However, repetitive activation of these muscles during walking imposes considerable stress on the periosteum and can favor the development of shin splints, which is supported by findings from epidemiologic studies.[37] Furthermore, the distal tendons of ankle invertors (particularly tibialis anterior and posterior) may become overstressed for decelerating excessive eversion motion and may lead to tendinopathies.[38] Finally, although less common, hypertrophy of leg muscles due to overexertion may elevate anterior and medial compartment pressure in the lower leg, which is a risk factor for compartmental syndrome.[39]

A limitation of this study was the impossibility to mask the participants and examiners. The potential clinical implications of the present study should also be considered carefully at this point. More studies are necessary to evaluate whether the effects of walking speed would be the same for individuals that present long-term excessive pronation due to biomechanical factors. Adaptation of body tissue and changes in movement strategies associated with long-term pronation might change how individuals respond to changes in walking speed. Importantly, however, the present method allowed us to demonstrate that the effect of gait velocity on foot motion is not general or context

independent. Such an effect might depend on the presence of biomechanical factors that change the efficiency of muscular action organized to respond to the demand of increasing walking speed.

Conclusions

The effect of gait speed on foot motion during gait seems to be modified in the presence of factors that induce excessive pronation. The magnitude of pronation was directly related to gait speed in the presence of a typical pronation-supination pattern. When excessive pronation was induced by inclined insoles, increases in gait speed were related to decreases in the magnitude of pronation. It is possible that individuals might use greater active control of foot motion at faster speeds in the presence of factors that induce excessive pronation, a strategy that could favor the development of musculoskeletal conditions.

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ERRATUM

In "The Design, Development, and Reliability Testing of a New Innovative Device to Measure Ankle Joint Dorsiflexion," by James Charles MHSc(Pod), which appeared in the September/October 2016 issue, Volume 106, Number 5, the author omitted conflict of interest and financial disclosures. The author applied for a patent for the device described in the article and therefore has both a conflict of interest and financial interest in the device. We regret this omission.