Effect of Static Foot Alignment on Plantar-Pressure Measures During Running

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Context: Altered foot dynamics due to malalignment of the foot may change plantar-pressure properties, resulting in various kinds of overuse injuries. Objective: To assess the effect of foot characteristics on plantar-pressure-related measures such as maximum pressure, maximum pressure–time, and pressure–time integral underneath the medial aspect of the foot during running. Design: Cross-sectional. Setting: Laboratory. Participants: 8 men and 17 women. Main Outcome Measures: Static non-weight-bearing rear-foot and forefoot alignment and navicular drop were measured. Plantar-pressure data were collected while subjects jogged at 2.6 m/s on a treadmill. Maximum pressure, time to maximum pressure, and pressure–time integral of the medial side of the foot were extracted for data analysis. Multiple-regression analysis was used to examine the effect of arch height and rear-foot and forefoot alignment on maximum pressure and pressure–time integral in the medial side of the foot. Results: In the medial rear-foot and midfoot regions, only rear-foot alignment had a significant effect on the variance of maximum pressure and pressure–time integral. There were no significant difference effects in the medial forefoot region. Conclusion: Rear-foot alignment was found to be a significant predictor of maximum plantar pressure and pressure–time integral in the medial rear-foot and midfoot regions. This indicates that control of rear-foot alignment may help decrease plantar pressure on the medial region of the foot, which may potentially prevent injuries associated with excessive rear-foot eversion.

Keywords: rear-foot valgus/varus, forefoot valgus/varus, pressure–time integral, overuse injury
results in an abnormal gait pattern characterized by compensatory rear-foot eversion. Therefore, this will result in an abnormal frontal-plane movement. It is believed that altered gait mechanics and intersegmental coupling relationships may change the center-of-pressure path during gait. With more everted rear-foot motion it is thought that center of pressure will shift more medially, which will further change plantar-pressure distributions and time to maximum pressure. Therefore, altered foot dynamics due to malalignment of the forefoot and rear foot may change plantar-pressure properties, as well.

While several studies have identified an association between plantar-pressure characteristics and injuries such as posterior tibialis dysfunction, functional ankle instability, and medial tibial-stress syndrome, there is no clear understanding of the relationships between foot-alignment factors, elevated plantar pressures in specific regions of the foot, and risk of specific injuries. Since foot alignment has the potential to change plantar-pressure measures in specific regions of the foot, the clear identification of the relationship between static foot alignment and plantar-pressure profiles is necessary before the performance of risk-factor studies. Moreover, understanding altered plantar-pressure patterns with associated changes in static foot measures may provide useful information for the prescription or design of interventions incorporating orthotics or motion-control shoes. To our knowledge, this study is the first to examine the relationship between static foot-alignment measures and plantar-pressure measures during jogging.

The purpose of this study was to assess the effect of foot characteristics on plantar-pressure-related measures such as maximum pressure, maximum pressure–time integral, and pressure–time integral underneath the medial aspect of the foot during running. Our rationale to analyze only the plantar pressures on the medial aspect of the foot was that increased medial-side plantar pressure has been reported as a risk factor for overuse injury. Furthermore, overuse injury that is induced by repetitive strain imposed by rear-foot evasion has often been reported to increase plantar pressure on the medial aspect of the foot.

**Methods**

**Subjects**

Pedhazur suggested a ratio of variables to cases of at least 5:1 to 10:1 for multiple-regression analysis. Since we have 3 predictor variables (navicular drop and rear-foot and forefoot alignment), 8 men and 17 women who were healthy and exercised regularly were recruited for this study (height 170.4 ± 7.4 cm, mass 59.5 ± 5.6 kg, age 21.4 ± 2.3 y). To be included, subjects had to engage in physical activity at least once a week. The exclusion criteria included history of lower extremity surgery, neurological pathologies, and occurrence of lower limb injury in the past 6 months. All subjects read and signed an informed-consent form before participating in the study. The study protocol was approved by the appropriate institutional review board.

**Instruments**

Navicular drop was measured with a Vernier height gage (Model 506-201, Mitutoyo Inc, Tokyo, Japan). A Quint Q65 treadmill (AIM, Sylmar, CA) was used for all trials of jogging. Plantar-pressure data were collected using the Pedar X in-shoe measurement system (Novel Inc, Munich, Germany) with a sampling rate of 100 Hz. Each 2.5-mm-thick Pedar-X insole contains 99 capacitive sensors with a maximum of 5-kPa resolution.

**Testing Procedures**

Before taking plantar-pressure measures during running, navicular drop and rear-foot and forefoot alignment were measured by a single examiner. Before data collection, the tester, who is a certified athletic trainer, was trained and reached an intratester reliability estimate of at least .80 (ICC) for all measurements. The intratester reliabilities of the navicular-drop test and rear-foot and forefoot alignment were ICC2,1 = .93, .87, and .88, respectively. Rear-foot and forefoot alignment were assessed in non-weight-bearing prone position using a plastic goniometer, and navicular drop was assessed in weight-bearing standing position using a Vernier height gage. Figure 1 depicts the definition of all foot-related measurements.

**Forefoot Varus/Valgus.** With the subject in prone position, forefoot varus/valgus alignment was measured per Oatis’s method. In subtalar-joint neutral position, the stationary arm of the plastic goniometer was placed along the first through fifth metatarsals while the movement arm was aligned perpendicular to a line bisecting the calcaneus. The angle between the movement arm and stationary arm was measured.

**Rear-Foot Varus/Valgus.** With the subject in a prone position, rear-foot varus/valgus alignment was measured per Oatis’s method. The rear-foot varus/valgus angle was measured when the subject was in non-weight-bearing subtalar neutral. Lines bisecting the calcaneus and the distal third of the lower leg were drawn before measurement. Subtalar neutral position was determined by palpation with the thumb and second finger placed on the dome of talus anterior to the ankle joint and the other hand holding the lateral aspect of the foot at metatarsal level in slight dorsiflexion. Once subtalar joint neutral position was identified (lateral and medial aspects of talar dome felt equally), the stationary arm of the goniometer was placed along the lower leg line and the movement arm along the calcaneal line. The acute angle between the 2 arms was read.

**Navicular Drop.** Arch height was assessed with the navicular-drop test using a height caliper.
Foot Alignment and Plantar Pressure

The navicular-drop test was performed in static standing position per the method of Bennett et al. The change in navicular height from standing subtalar neutral to standing weight-bearing neutral was measured with a Vernier height gage.

After all the static measurements were collected, subjects were fitted with a pair of New Balance cross-training sneakers (model number WX755WB, Boston, MA). They were fitted with the proper-size shoes and in-shoe plantar-pressure insoles. The insoles were placed between the shoe and the subject’s foot. The subject was positioned on the treadmill and instructed to walk for 30 seconds at preferred speed. Once he or she was comfortable, the examiner accelerated the treadmill to 2.6 m/s (6 miles/h) for a minute for the subject to get used to the speed. We chose this speed because average self-selected jogging speed from the normative data of our gait laboratory is 2.6 m/s. Then the subject was asked to take a 30-second break before data collection. Three 10-second trials were then recorded (100 Hz) as the subject continuously jogged at 2.6 m/s. Plantar-pressure data from the left and right feet, which were collected by the Pedar X in-shoe measurement system while subjects were jogging, were then transmitted via Bluetooth to a laptop computer and saved. Only right-side plantar-pressure data were analyzed for this study.

Data Reduction

Novel Automask and Industrial software (Novel Inc, Munich, Germany) were used to calculate maximum pressure and pressure–time integral in each of 9 areas of the foot. The 9 areas were medial rear foot, lateral rear foot, medial midfoot, lateral midfoot, medial forefoot, middle forefoot, lateral forefoot, great toe, and the rest of the toes (Figure 2). Among all these masks, medial rear-foot (M1), midfoot (M3), and forefoot regions (M5) were analyzed in this study. The definition of maximum pressure was the highest pressure observed under the specific mask throughout the stance phase of the gait cycle, and the definition of pressure–time integral was the total area under the pressure curve observed under the specific mask throughout the stance phase.

Figure 1 — Static foot measurements. (a) Forefoot alignment. (b) Rear-foot alignment. (c) Navicular height. Positive value indicates valgus alignment of forefoot and rear foot.

Figure 2 — Definition of plantar foot regions.

Statistical Analysis

SPSS 14.0 was used for statistical analysis. The independent variables of this study were navicular drop and rear-foot and forefoot alignment, and the dependent variables were maximum pressure, time to maximum pressure, and pressure–time integral in the medial rear foot, midfoot, and forefoot. Stepwise multiple-regression analysis was used to examine the effect of arch height and rear-foot and forefoot alignment on maximum pressure, time to maximum pressure, and pressure–time integral in the medial rear-foot and forefoot masks. The alpha level was preset to $P < .05$ to determine statistically significant differences in this test.
Results

The means and standard deviations of rear-foot and forefoot alignment and navicular drop were $3.56^\circ \pm 1.50^\circ$, $1.28^\circ \pm 1.43^\circ$, and $4.99 \pm 2.47$ mm, respectively. Table 1 shows the means and standard deviations of pressure-related variables.

Table 2 illustrates the correlation between rear-foot and forefoot and pressure measures. Stepwise multiple-regression analysis revealed that in the medial rear-foot region, only rear-foot alignment had a significant effect on the variance of maximum pressure ($F_{1,23} = 7.71, P = .01$). Rear-foot alignment accounted for 25.1% of the variance of maximum pressure ($R = -.501, R^2 = .251$). Rear-foot alignment also had a significant effect on the variance of the pressure–time integral ($F_{1,23} = 13.25, P < .01$). It accounted for 36.5% of variance in the pressure–time integral ($R = -.605, R^2 = .365$).

Figure 3 demonstrates in a scatter plot the relationship between rear-foot alignment, maximum pressure, and pressure–time integral in the rear-foot region. In the medial rear-foot region, rear-foot alignment accounted for 25.1% of the variance of maximum pressure ($R = -.501$) and 36.5% of the variance of pressure–time integral ($R = -.605$).

Figure 4 shows the scatter plot of the relationship between rear-foot alignment, maximum pressure, and pressure–time integral in the medial midfoot region. In the medial midfoot region, rear-foot alignment had a significant effect on the variance of maximum pressure ($F_{1,23} = 7.26, P = .013$) and the maximum pressure–time integral ($F_{1,23} = 6.34, P = .019$). Rear-foot alignment accounted for 24% of the variance of maximum pressure ($R = -.490$) and 21.6% of the variance of the pressure–time integral ($R = -.465$).

There were no significant predictors for the forefoot pressure measures.

Discussion

To date, there have been no studies investigating the relationship between static foot alignment and plantar-pressure measures during running. However, in overuse injuries, the alignment of the foot has been considered a risk factor due to altering normal gait characteristics.

Table 1  Pressure Measures in Each Plantar Foot Region, Mean ± SD

<table>
<thead>
<tr>
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<th>Medial rear foot</th>
<th>Medial midfoot</th>
<th>Medial forefoot</th>
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</thead>
<tbody>
<tr>
<td>Maximum pressure (KPa)</td>
<td>234.05 ± 66.45</td>
<td>222.58 ± 61.85</td>
<td>280.81 ± 103.89</td>
</tr>
<tr>
<td>Maximum pressure–time (%)</td>
<td>8.49 ± 6.04</td>
<td>32.80 ± 3.43</td>
<td>50.10 ± 3.99</td>
</tr>
<tr>
<td>Pressure–time integral (KPa/s)</td>
<td>19.55 ± 6.63</td>
<td>19.75 ± 7.26</td>
<td>42.45 ± 15.95</td>
</tr>
</tbody>
</table>

Table 2  Correlation Matrix of Foot Alignments and Pressure Measures

<table>
<thead>
<tr>
<th></th>
<th>Rear-foot alignment</th>
<th>Forefoot alignment</th>
<th>Navicular drop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rear-foot alignment</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Forefoot alignment</td>
<td>.289</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Navicular drop</td>
<td>-.224</td>
<td>.201</td>
<td>—</td>
</tr>
</tbody>
</table>

Medial rear foot

- maximum pressure: -.501*  -.135  -.102
- maximum pressure–time: -.139  .240  .247
- pressure–time integral: -.605*  -.061  .060

Medial midfoot

- maximum pressure: -.490*  -.114  -.022
- maximum pressure–time: .020  .222  .204
- pressure–time integral: -.465*  -.088  .145

Medial forefoot

- maximum pressure: .158  .248  -.103
- maximum pressure–time: -.241  -.258  -.031
- pressure–time integral: .146  .155  -.080

*Statistically significant, $P < .05$. 

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Figure 3 — Correlation between rear-foot alignment and medial rear-foot pressure-related variables. (a) Maximum pressure. (b) Pressure–time integral.

Figure 4 — Correlation between rear-foot alignment and medial midfoot pressure variables. (a) Maximum pressure. (b) Pressure–time integral. R = –.465; R² = .216.
Our results suggested that the alignment of the foot might contribute to changes in plantar-pressure patterns during running. These findings may improve the understanding of normal gait mechanics in terms of the relationship between foot alignment and plantar-pressure patterns. Furthermore, they may provide scientific evidence to inform clinical decisions related to orthotic and shoe prescription to treat various lower extremity problems.

Our results demonstrated that there were specific relationships among static foot alignment and plantar-pressure measures. These can be summarized as follows: Static valgus rear-foot alignment increased medial rear-foot and midfoot plantar pressures and increased the sum of all plantar loading during the stance phase of the gait cycle on the medial rear foot and midfoot.

We hypothesized that all the static-alignment measures including rear-foot angle, forefoot angle, and navicular drop would be significant predictors of the pressure measures at the medial rear foot. However, static rear-foot alignment was the only significant predictor of maximum pressure and the pressure–time integral in the medial rear foot, accounting for 25.1% and 36% of the variance, respectively. A negative correlation between static rear-foot alignment and maximum pressure at the medial rear-foot region indicates that a more valgus static alignment of the rear foot was associated with increased plantar pressure in the medial rear-foot region during running. Static valgus alignment of the rear foot at initial contact may cause increased plantar pressure on the medial rear foot during early stance. Static valgus position of the rear foot in weight bearing has been associated with decreased arch height.15–17 This is a typical property of flexible feet such as pes planus. Along with static rear-foot valgus, the decreased arch height during weight-bearing conditions may shift the center of pressure medially and results in increased plantar pressure on the medial region of the foot.

The total loading time on the medial portion of the foot will be increased with static valgus rear-foot alignment. The moderate to high correlation between the pressure–time integral of the medial rear foot and static rear-foot alignment is indicative of this finding. Rear-foot alignment accounted for 36% of the total amount of the pressure–time integral. This result indicates that valgus rear-foot alignment affects the amount of pressure applied to the medial rear foot throughout the entire stance phase. Since overuse injuries have been reported to be associated with increased plantar pressure on the medial side of the foot,7,8 interventions that can neutralize valgus alignment of the foot are able to decrease medial plantar pressure.26 According to Willems et al.,7,8 increased medial pressure results in increased rear-foot pronation, which is also an identified risk factor for lower extremity overuse injury. Therefore, control of valgus alignment of the foot may help prevent overuse injury. However, to accurately understand the dynamic posture of the foot in initial foot-contact phase and during midstance phase, further study that includes motion analysis of the foot should be conducted along with plantar-pressure measurement.

We also hypothesized that all 3 static foot alignments would be predictors of pressure measures at the medial midfoot. However, rear-foot alignment was the only significant predictor of maximum pressure and the pressure–time integral in this region, accounting for 24% and 21.6%, respectively. Rear-foot valgus in weight bearing is believed to be associated with decreased arch height.15–17 Although frontal-plane rear-foot kinematics and dynamic arch height were not measured in this study, the high correlation between static rear-foot alignment and medial midfoot plantar pressure indicated that there might be decreased arch height during the midstance phase to increase medial midfoot plantar pressure.

This finding also has clinical importance regarding the prevention of overuse injuries. One strategy to prevent such injuries may include preventing medial longitudinal arch collapse. Athletic trainers and health care providers can use arch supports or other interventions such as low-dye tape on the foot to reduce medial midfoot pressures and may subsequently reduce the amount of rear-foot eversion during gait.27 In addition to the clinical implications of our findings that we have discussed, clinicians should note that there are limitations to applying our findings directly to interventions. There are inconsistent findings regarding static and dynamic foot posture in the literature. Nigg et al.,28 Kernozek and Ricard,29 and McPoil and Cornwall30 reported that static alignment measures are associated with rear-foot movement during gait. On the other hand, Boozer et al.31 reported that height of the medial longitudinal arch is strongly related to rear-foot motion. Therefore, even though our study found strong to moderate relationships between static foot posture and medial plantar pressure, these findings may not translate to dynamic posture during the stance phase of the gait cycle. Nonetheless, in the clinic, static foot measures are more feasible than dynamic foot-posture measures because of the high cost of motion analysis and the limited amount of clinician time to perform gait analysis.

In our study, we did not collect 3-dimensional joint kinematics to confirm the relationship between 3-dimensional foot motion and plantar pressure. Even though we do have anecdotal evidence that increased medial plantar pressure may increase rear-foot eversion, we recognize that to fully understand the relationships between static foot alignment, plantar-pressure distribution, and rear-foot motion, additional research incorporating estimates of rear-foot eversion and dynamic arch height during gait, as well as plantar-pressure measure, is required. Nonetheless, the findings of the current study suggest that controlling static rear-foot alignment may decrease medial rear-foot and midfoot plantar pressure during gait.

**Conclusion**

Rear-foot alignment was found to be a significant predictor of the maximum plantar pressure and pressure–time integral in the medial rear-foot and midfoot regions. This
indicates that control of rear-foot valgus foot alignment may aid in the prevention and treatment of overuse injuries. Our results also suggest the need to examine rear-foot eversion and dynamic arch height to clearly understand the underlying mechanism of increased maximum pressures on the rear foot and midfoot with increased rear-foot valgus alignment.

References


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