Background: Research on foot orthoses has shown that their effect on the kinematics of the rearfoot is variable, with no consistent patterns of changes being demonstrated. It has also been hypothesized that the mechanical effect of foot orthoses could be subject specific. The purpose of our study was to determine if maximally pronated feet have a different response to frontal plane wedging of foot orthoses than do nonmaximally pronated feet during static stance.

Methods: One hundred six feet of 53 healthy asymptomatic subjects were divided into two groups (maximally pronated and nonmaximally pronated) on the basis of their subtalar joint rotational position during relaxed bipedal stance. Functional foot orthoses were constructed for each subject and the relaxed calcaneal stance position was measured while standing on five separate frontal plane orthosis wedging conditions, 10° valgus, 5° valgus, no wedging, 5° varus, and 10° varus, to assess changes in calcaneal position.

Results: Relative to the no-wedging condition, there were statistically significant differences \((P < .05)\) in calcaneal position between the maximally pronated and the nonmaximally pronated feet with the 10° valgus and the 10° varus wedging conditions. No significant differences in calcaneal position were found with the 5° varus and the 5° valgus wedging conditions.

Conclusions: Our study shows that the response to foot orthoses is variable between individuals. Maximally pronated subjects do not exhibit the same response to frontal plane wedging of foot orthoses as do nonmaximally pronated with 10° wedging. Intrinsic biomechanical factors such as subtalar joint position may influence the response to foot orthoses. (J Am Podiatr Med Assoc 99(1): 13-19, 2009)
tion. Other studies have found significant changes in the transverse plane motion of the leg relative to the foot with the use of foot orthoses. Although the changes in rearfoot motion or tibial rotation have been statistically significant in many studies, the angular changes remain quite small, at about 2° to 3°, in most studies.

One of the problems in trying to compare the results of studies of foot orthoses is the general lack of common methodology and relatively small number of study participants. Some authors have noticed that changes in the kinematic response are highly variable from one subject to the other, which suggests that the response to the use of foot orthoses could be subject specific. In this regard, it could be possible that intrinsic biomechanical factors within the foot and lower extremity of the subject are responsible for the highly variable individual response to foot orthoses.

Because of the need for more research on the mechanical effect of orthoses on different foot types, we conducted a study to measure the positional response of the rearfoot to varying degrees of frontal plane orthosis wedging in two study groups: those with maximally pronated feet and those with nonmaximally pronated feet. The goal of the study was to determine whether the rotational position of the subtalar joint has a mechanical effect on how frontal plane wedged orthoses may or may not reposition the rearfoot into a new angle of alignment to the ground. In this fashion, the study was designed to not only directly measure the effect of frontal plane wedging on different foot types, but was also designed to allow further insight into how externally applied orthosis reaction forces may be affected by the internal forces within the foot that resist changes in rearfoot motion.

**Methods**

A total of 53 volunteers were enrolled in the study. The study group included healthy asymptomatic volunteers who were interviewed to determine if they met the inclusion criteria. The exclusion criteria for the study included the presence of pain or evident gross deformity of the foot and lower extremity, treatment with insoles or braces during the past year, inflammatory diseases, connective-tissue disorders, a history of foot and ankle surgery, or past serious trauma to the foot and lower extremities. Written consent was obtained from all study participants after a verbal and written explanation of the project.

Participants were divided into two groups on the basis of the subtalar joint rotational position of the participants during relaxed bipedal stance: a) maximally pronated, and b) nonmaximally pronated. The determination of whether the participants’ feet were maximally pronated was accomplished by using the maximum pronation test. With the patients standing in their angle and base of gait, participants were asked to pronate their feet at the same time by lifting up the lateral edges of their feet without flexing their knees. For inclusion in the nonmaximally pronated group, there must have been 3° or more of difference between the relaxed calcaneal stance position (RCSP) and the maximally pronated subtalar joint position in the frontal plane. Conversely, if there were 2° or less of difference between the RCSP and the calcaneal position in the maximally pronated subtalar joint position, the participant was assigned to the maximally pronated group.

Orthoses for each participant were fabricated according to standard orthosis fabrication techniques. A plaster of Paris negative cast was made of both feet using the neutral suspension casting technique in a nonweightbearing position (Fig. 1). All negative impression casts were balanced so that the calcaneal bisection was perpendicular when the positive cast was constructed. The positive casts were modified by using the standard protocol for functional foot orthoses as described by Anthony. These modifications include a lateral expansion to allow soft-tissue expansion on weightbearing and medial addition to...
improve first ray function and avoid medial arch irritation (Fig. 2). The shells of the orthoses were made of 4.0 mm polypropylene; the rearfoot posts were made of high-density ethyl vinyl acetate and were constructed flat, without a biplanar grind.

The calcaneal stance position of the subjects was measured with the orthosis and with different types of wedging conditions to assess changes in calcaneal position. One physician (J.M.R.M.) drew the bisection lines on the posterior aspect of the calcaneus and made all of the measurements on each of the participants. A coffee-stirrer stick was adhered to the posterior calcaneus so that it was parallel to and in line with the calcaneal bisection in order to reduce the measurement error. A goniometer was used to record the measurements of the frontal plane position of the calcaneus at each orthosis testing position to within 1° accuracy. The five testing positions measured were: 1) no wedging (orthosis only), 2) orthosis with valgus wedging of 5°, 3) orthosis with valgus wedging of 10°, 4) orthosis with varus wedging of 5°, and 5) orthosis with varus wedging of 10°. The wedges were placed under both the orthosis and under the forefoot and rearfoot of the participant so that the whole foot of the subject was resting on both the orthosis and the wedge (Fig. 3). Measurements of the five orthosis-wedging conditions were randomized in three rounds among participants to avoid an order effect. For data analysis, the mean of three random measurements were used for each condition. The same orthosis-wedging condition was used to simultaneously position and measure both feet.

Results were expressed as mean ± standard deviation. A nonpaired Student t test and χ² test was calculated for age and sex between maximally pronated and nonmaximally pronated groups. The change of RCSP in the four wedging conditions (ie, 10° valgus, 5° valgus, 5° varus, 10° varus) was compared, using the no-wedging condition as the baseline. A nonpaired Student t test was used to compare differences in the change of RCSP between maximally pronated and nonmaximally pronated feet in the four conditions measured (P ≤ .05). Because left and right feet were assigned to different groups in some individuals and because Pearson correlation factors between left and right feet were mostly low (r < 0.5) for the variables studied, both feet were analyzed. Statistical analysis was performed with SPSS software, version 12.0 (SPSS, Chicago, Illinois).

**Results**

A total of 106 feet (53 participants) were included in the study. Of the 53 participants, 23 were male (43.4%) and 30 were female (56.6%). The participant ages ranged from 20 to 52 years (mean ± SD, 27.47 ± 7.24 years). The mean ± SD age of the males was 28.74 ± 7.94 and the mean ± SD age of the females was 26.50 ± 6.56. Seventy-one feet were included in the nonmaximally pronated group and 35 feet in the maximally pronated group. Table 1 summarizes the age and sex data of the participants in the maximally pronated and nonmaximally pronated groups. There were no statistically significant differences in age (P = .151) and sex (P = .450) between the maximally and nonmaximally pronated groups.

Table 2 summarizes the difference in calcaneal stance position by comparing the no-wedging condi-
tion to the wedging conditions in maximally pronated and nonmaximally pronated feet. There were statistically significant differences in the calcaneal stance position with $10^\circ$ valgus wedging ($P = .013$) and with $10^\circ$ varus wedging ($P = .011$) between the maximally pronated and nonmaximally pronated groups. Participants in the nonmaximally pronated group exhibited greater changes in RCSP with the $10^\circ$ valgus condition than did the nonmaximally pronated group ($4.90^\circ$ versus $3.49^\circ$). The nonmaximally pronated group also exhibited greater changes in RCSP with the $10^\circ$ varus condition than did the nonmaximally pronated group ($5.91^\circ$ versus $4.63^\circ$). There were no statistically significant differences with the $5^\circ$ varus wedging condition and with the $5^\circ$ valgus wedging condition between the maximally pronated and nonmaximally pronated groups.

**Discussion**

Studies investigating the kinematic effect of foot orthoses have shown varied results, although most of them have reported that foot orthoses are effective in altering rearfoot motion. Heiderscheit et al. cited that rearfoot motion measurements may be altered not only because of the type of orthosis used but also because of the measurement system, marker placement, skin movement artifact, variable subject groups, individual response of the participant to the orthosis, and because of lack of statistical power. For that reason, it is difficult to extract valid conclusions from the studies measuring the effect of foot orthoses on kinematic variables of the foot and lower extremity. At the same time, other authors have suggested that changes in skeletal alignment to foot orthoses are subject specific, or, in other words, the mechanical effect of a foot orthosis is variable and dependent not only on the subject but also on the individual mechanical characteristics of each of the subjects’ feet. Therefore, studying specific groups of patients and their response to foot orthoses is a reasonable method to gain further insight into the complex mechanisms behind the responses of individuals to foot orthoses.

Our study used two study groups, maximally pronated and nonmaximally pronated feet, and we found significant differences between the maximally pronated and nonmaximally pronated groups regarding how the RCSP changed with the $10^\circ$ varus and $10^\circ$ valgus orthosis wedging conditions, at $1.27^\circ$ and $1.40^\circ$, respectively. In other words, more pronated feet showed less change in their RCSP with $10^\circ$ varus and valgus wedging than did the nonmaximally pronated feet. Our finding that maximally pronated feet everted less than the nonmaximally pronated feet in response to the $10^\circ$ valgus wedge is logical since the maximally pronated feet are already at their end range of pronation motion during relaxed bipedal stance. Therefore, the maximally pronated feet would not be expected to be able to evert much further than the maximally pronated position with application of an eversion force from a valgus-wedged foot orthosis. However, in regard to the $10^\circ$ varus wedging condition, the mechanical explanation of why the maximally pronated feet inverted less in response to the $10^\circ$ varus-wedged orthosis than did the nonmaximally pronated feet is not readily apparent.

The most reasonable explanation for the differences between how the maximally pronated and nonmaximally feet responded to the $10^\circ$ varus wedging condition are contained within the mechanical concepts of the subtalar joint axis location and rotational equilibrium theory of foot function. In this theory, the spatial location of the subtalar joint axis is proposed to significantly influence not only how the foot functions during weightbearing activities but also how the foot responds to external subtalar joint supination.

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**Table 1. Characteristics of Participants in the Two Study Groups**

<table>
<thead>
<tr>
<th>Study Groups</th>
<th>Maximally Pronated Feet</th>
<th>Nonmaximally Pronated Feet</th>
<th>$P$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total no. of feet</td>
<td>35</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>Age (y)</td>
<td>28.91 ± 9.65</td>
<td>26.76 ± 5.64</td>
<td>.151</td>
</tr>
<tr>
<td>Sex</td>
<td>Male (n = 46) 17 29 .450</td>
<td>Female (n = 60) 18 42 .450</td>
<td></td>
</tr>
</tbody>
</table>

*Participants were divided into study groups on the basis of subtalar joint rotational position during relaxed bipedal stance. One hundred six feet were included in the study.*

*Data are presented as mean ± SD.*

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**Table 2. Changes in Relaxed Calcaneal Stance Position with Different Types of Wedging**

<table>
<thead>
<tr>
<th>Wedging Type</th>
<th>Nonmaximally Pronated</th>
<th>Maximally Pronated</th>
<th>Difference</th>
<th>$P$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^\circ$ varus</td>
<td>–4.90°</td>
<td>–3.49°</td>
<td>1.40°</td>
<td>.013°</td>
</tr>
<tr>
<td>$5^\circ$ varus</td>
<td>–2.88°</td>
<td>–2.63°</td>
<td>0.24°</td>
<td>.576°</td>
</tr>
<tr>
<td>$5^\circ$ varus</td>
<td>3.15°</td>
<td>2.45°</td>
<td>0.69°</td>
<td>.081°</td>
</tr>
<tr>
<td>$10^\circ$ varus</td>
<td>5.91°</td>
<td>4.63°</td>
<td>1.27°</td>
<td>.011°</td>
</tr>
</tbody>
</table>

*Note: Positive values indicate inversion motion of rearfoot compared to the no-wedging condition.*

*The wedging conditions listed were compared to the no-wedging condition.*

*$P < .05$.*
nation and pronation moments, such as would be applied by the foot orthoses used in this study. Payne et al\textsuperscript{28} showed that more external supination force was required to supinate the subtalar joint from a pronated position when the foot had a more medially deviated subtalar joint axis. The more medial location of the subtalar joint axis, the greater will be the external subtalar joint pronation moments from ground reaction force and, therefore, the more likely that the foot will be pronated while in static stance and during gait.\textsuperscript{27, 29, 40}

In our study, if we can assume that the feet that were in the maximally pronated position were also the feet that had the greatest external subtalar joint pronation moments caused by ground reaction force, then these increased external pronation moments may also be the reason why there was a difference in response between the maximally pronated and nonmaximally pronated feet with the 10° varus wedging condition. Since maximally pronated feet are more likely to be medially deviated at the subtalar joint axis in static stance than are nonmaximally pronated feet,\textsuperscript{37} maximally pronated feet may need more external supination moment to achieve the same correction when compared to nonmaximally pronated feet. Although there were differences with the use of 5° valgus and varus wedging condition between groups, these differences were small (0.24° and 0.69°, respectively), and not statistically significant. It is possible that the 5° orthosis wedging condition did not show significant changes in rearfoot position since the amount of wedging was too small to exert sufficient external subtalar joint supination moment or sufficient external subtalar joint pronation moment to invert or evert the rearfoot, respectively. However, results with the 5° varus wedging condition showed a trend toward significance ($P = 0.081$). Despite the small changes observed (0.69°), we believe that a larger sample in the nonmaximally pronated group would have showed significant differences in the correction obtained with the 5° varus wedging condition between the maximally pronated and nonmaximally pronated groups.

The concept that foot orthoses and wedging may change the position of the rearfoot by changing the forces and moments acting across the subtalar joint is a reasonable assumption, especially considering the recent research that shows that foot orthoses significantly affect foot and lower-extremity kinetics.\textsuperscript{20, 21, 28, 29} Williams et al\textsuperscript{28} found that although standard and inverted orthoses do not have any significant effect on the kinematic variables, there were significant changes in the rearfoot and knee moments with the use of the inverted orthoses. Therefore, changes in moments may need to be high enough to produce measurable changes in rearfoot position since small changes in moments may not be sufficient to produce significant rearfoot positional changes. This would also help to explain the relatively small changes in calcaneal position with the 5° varus and valgus wedging conditions.

Nawoczenski et al\textsuperscript{15} compared the relative response of two different types of foot structure characteristics to foot orthoses. Individuals were classified into either low-rearfoot or high-rearfoot profile groups on the basis of radiographic measurements of the lateral calcaneal inclination, lateral talometaatarsal, and anteroposterior talometatarsal angles. Their findings showed no differences in the amount of correction achieved with orthoses between groups. Individuals in both groups responded similarly to orthoses, which is in contrast to our results. One possible reason for this difference could be that their subjects were classified into low- or high-rearfoot profile groups on the basis of static radiographic parameters that may not necessarily reflect subtalar joint rotational position as was the case in our study. In addition, the orthoses used in their study were not made with varus or valgus corrections. Since our study showed that 10° of wedging of custom foot orthoses was necessary to observe differences between maximally pronated and nonmaximally pronated feet, then it is possible that the study by Nawoczenski et al\textsuperscript{15} did not have sufficient wedging within their orthoses to produce significant kinematic changes in their subjects.

To our knowledge, ours is the first study that compares the effect of foot orthoses on subjects who have been divided into groups on the basis of their subtalar joint rotational position and that demonstrates that subtalar joint rotational position during relaxed bipedal stance may influence the subject's mechanical response to foot orthoses. These results have important implications for the design of future research intended to assess the kinematic effects of foot orthoses on the foot and lower extremity. Considering the results of our study, it seems likely that intrinsic biomechanical aspects of each foot, such as subtalar joint rotational position, could be responsible for the subject-specific response to foot orthoses seen in previous studies.\textsuperscript{25, 27, 31}

Extrapolation of the results of our study to the clinical environment should be carried out cautiously because of certain limitations of the research. First, even though calcaneal stance position measurements have been shown to have a good to excellent intrarater reliability in several studies,\textsuperscript{41-43} no studies have assessed the reliability of measurements of calcaneal position with orthoses. Therefore, we have assumed that our measurement reliability with foot orthoses is the same as those studies where calcaneal position...
was measured without the subject standing on orthoses. Second, the static nature of our study may not necessarily represent the mechanical behavior of the foot during dynamic activities, such as walking or running. We are considering conducting similar research in the dynamic environment of walking to see if similar changes in rearfoot position are noted with varus- and valgus-wedged foot orthoses. Also, measurements in our study were made in double-limb static stance where approximately half the body weight was applied to each foot, whereas, in walking during the middle of midstance, the ground reaction force approximates body weight. This ground reaction force discrepancy between the present study and walking certainly may prevent direct extrapolation to the dynamics of walking. Third, another possible limitation of the study was that all foot orthoses made in the study were made of the same shell thickness (ie, 4 mm polypropylene) regardless of the weight or foot morphology of the participant. The use of 4 mm polypropylene as a standard shell thickness may have allowed participants with different body weights and foot shapes to deform the plates of the orthosis differently than other participants. However, a case could also be made that by standardizing the orthosis shell to the commonly used 4 mm shell thickness, another variable that may have influenced the study results was eliminated. Finally, since the study was composed of asymptomatic volunteers, the participants enrolled in the study may not have responded to the orthoses in the same way that an injured patient may have responded. It is recommended that further studies be conducted that compare asymptomatic to symptomatic individuals to see if these subject groups would show differing mechanical responses to foot orthoses.

Conclusions

Our study shows that the change in calcaneal position in response to foot orthoses is variable between individuals at 10° of varus and valgus wedging in static conditions. Maximally pronated feet responded with less rearfoot rotation than did nonmaximally pronated feet at 10° of orthosis wedging. However, no differences were found between maximally pronated and nonmaximally pronated feet at 5° of orthosis wedging. Therefore, intrinsic biomechanical factors of the participants, such as subtalar joint rotational position, seem to influence the static response of the participant to foot orthoses at 10° of wedging. The use of 5° varus and valgus wedges do not seem to cause a difference in response between maximally pronated and nonmaximally pronated feet. The results of our study indicate that, in the future, subtalar joint rotational position should be taken into consideration when planning kinematic studies regarding the mechanical effects of foot orthoses.

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Conflict of Interest: None reported.

References


