Effect of a Metatarsal Pad on the Forefoot During Gait

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**Background:** Metatarsal pads are frequently prescribed for patients with metatarsalgia to reduce pain under the distal metatarsal heads. Several studies showed reduced pain and reduced plantar pressure just distal to the metatarsal pad. However, only part of the pain reduction could be explained by the decrease in plantar pressure under the forefoot. Therefore, an alternative hypothesis is proposed that pain relief is related to a widening of the foot and the creation of extra space between the metatarsal heads. This study focused on the effect of a metatarsal pad on the geometry of the forefoot by studying forefoot width and the height of the second metatarsal head.

**Methods:** Using a motion analysis system, 16 primary metatarsalgia feet and 12 control feet were measured when walking with and without a metatarsal pad.

**Results:** A significant mean increase of 0.60 mm in forefoot width during the stance phase was found when a metatarsal pad was worn. During midstance, the mean increase in forefoot width was 0.74 mm. In addition, walking with a metatarsal pad revealed an increase in the height of the second metatarsal head (mean, 0.62 mm). No differences were found between patients and controls.

**Conclusions:** The combination of increased forefoot width and the height of the second metatarsal head produced by the metatarsal pad results in an increase in space between the metatarsal heads. This extra space could play a role in pain reduction produced by a metatarsal pad. (J Am Podiatr Med Assoc 102(1): 18-24, 2012)

Metatarsalgia is defined as pain on the plantar side of the distal metatarsal heads and is subdivided into primary and secondary metatarsalgia based on the underlying cause. Independent of the cause, metatarsalgia usually arises due to exceeding the pressure tolerance of the focal tissue under the metatarsal heads. Metatarsal pads (MPs) are frequently prescribed for the nonoperative management of metatarsalgia. The MPs can be positioned directly on the sole of the shoe or incorporated into an insole. To reduce the plantar pressure, an MP has to be placed just proximal to the distal head of the metatarsal bone that causes the pain. Kang and colleagues demonstrated that the use of an MP results in pain reduction in patients with primary metatarsalgia. Moreover, they found a significant correlation of 0.77 between the decrease in plantar pressure under the metatarsal heads and a reduction in subjective pain scores. However, Postema and colleagues found no significant correlation between the decrease in plantar pressure and the reduction in pain in patients with primary metatarsalgia. From this we can conclude that in addition to pressure reduction, other mechanisms must contribute to pain reduction in patients with metatarsalgia.

Because there is a relation between foot deformities and metatarsalgia, forefoot geometry is another mechanism that could be affected by MPs. Two studies have already demonstrated that insoles affect the static foot geometry in patients with foot complaints. Also, a study by Kouchi and colleagues demonstrated an increase of 2 mm in the cross-sectional shape of the forefoot from the first peak to the midstance valley of the vertical ground reaction force. From a biomechanical view,
MPs can alter the shape of the transversal arch in two ways (Fig. 1). First, if the distance between the metatarsal bones remains constant, the MP narrows the forefoot (elevated fixed chain). Second, if the distance between the metatarsal bones increases (ie, broadening of the forefoot), the MP pushes the metatarsal bones upwards and to the side.

To our knowledge, no previous studies have been conducted on the biomechanical effects of an MP on the foot. The main goal of this study was to determine the effect of an MP on spreading of the forefoot. We hypothesized that an MP causes an increase in forefoot width, indicating an increased space between the metatarsal heads. In addition to forefoot spreading, the effect of an MP on plantar pressure distribution will be studied in detail using a spatial normalization procedure.13

Materials and Methods

Participants
Six healthy individuals (three men and three women) and 11 patients with primary metatarsalgia (two men and nine women) participated in this study. All of the patients reported pain in one or both feet. Only feet for which the patients reported pain were measured (18 patient feet). Patients with evident foot deformities, such as claw or hammer toes, were excluded. For participants in the control group, both feet were measured (12 control feet). None of the controls had a history of foot complaints or foot deformities. Owing to technical problems, two feet in the patient group could not be used. Table 1 shows the characteristics of the participants. All of the participants participated voluntarily and signed an informed consent form before the start of the study. The study was performed in accordance with the Declaration of Helsinki.

Metatarsal Pad
Teardrop-shaped MPs made of polyurethane foam of the same size (55 mm long, 38 mm wide, and 10 mm in maximal height, at 22 mm from the distal end) were used. An experienced physical therapist placed the pads just proximal to the distal head of the second metatarsal bone, the most optimal position according to Hsi and colleagues.3 Two-sided adhesive tape was used to attach the MP under the foot.

Study Design
An eight-camera motion analysis system (Vicon Motion Systems Ltd, Oxford, England) and a 13-mm-thick pressure plate (footscan; RSscan, Olen, Belgium) on top of a force plate embedded in the floor (Kistler Instruments, Winterthur, Switzerland) were used to study the effect of an MP on the foot. Motion analysis was performed to detect changes in forefoot geometry, in particular forefoot spreading. Pressure measurements were performed to quantify the plantar pressure distribution under the foot. Afterward, the plantar pressure distribution was studied to evaluate MP placement. All of the participants performed five trials in each condition (walking with or without an MP). The starting condition was randomized. All of the trials were conducted with

Table 1. Characteristics of the Study Participants by Group

<table>
<thead>
<tr>
<th></th>
<th>Control Feet</th>
<th>Patient Feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex (F:M [No.])</td>
<td>6:6</td>
<td>14:4</td>
</tr>
<tr>
<td>Height (mean ± SD [cm])</td>
<td>177.5 ± 14.4</td>
<td>171.8 ± 7.8</td>
</tr>
<tr>
<td>Age (mean ± SD [years])</td>
<td>30.0 ± 9.8a</td>
<td>42.6 ± 10.3a</td>
</tr>
<tr>
<td>Weight (mean ± SD [kg])</td>
<td>72.2 ± 13.4</td>
<td>77.0 ± 10.3</td>
</tr>
<tr>
<td>Shoe size (mean ± SD [EU])</td>
<td>41.3 ± 3.2</td>
<td>39.9 ± 2.6a</td>
</tr>
</tbody>
</table>

* *A significant difference between control feet and patient feet.
bare feet at preferred walking speeds. A trial consisted of walking six to eight steps across the walkway according to a three-step protocol.

For the motion measurements, markers with a diameter of 9.5 mm were attached on the medial side of the first metatarsal head and base, and on the lateral side of the fifth metatarsal head and base (Fig. 1). These markers were placed perpendicular to the sagittal plane of the metatarsal bones. In addition, markers were placed on top of the second metatarsophalangeal joint and at the back of the heel. All marker data were registered at a sample frequency of 200 Hz. The force plate, embedded in the floor, measured ground reaction forces at a sample frequency of 2,400 Hz. The plantar pressure data were collected at 500 Hz, and the sensor density of the pressure plate was 2.6 sensors per square centimeter.

A control study was performed to check the accuracy of the motion analysis system because we expected to demonstrate small changes in forefoot geometry. The purpose was to demonstrate the ability of the system to detect changes in distance between two markers of 0.1 and 0.5 mm. The markers were placed on the outside jaws of a vernier caliper. Subsequently, the distance between the markers (approximately 90 mm) was five times increased by 0.1 mm and subsequently by 0.5 mm. Motion measurements were performed while the vernier caliper was swung for 10 sec (2,000 samples) in the force plate area for each condition.

To rule out the effect of skin movement on the main outcome measure (ie, forefoot width), we performed anteroposterior radiography of one foot (of a participant in the control group) with an MP attached underneath and without an MP. Although, the main interest was the effect of an MP during walking, the radiograph had to be performed in a static situation. During radiography, the participant was positioned in the midstance phase of gait whereby the contralateral leg was used to keep balance. Afterward, the radiologist measured the distance between the first and fifth metatarsal heads. The distance was measured three times in each condition using clear reference points on the metatarsal bones.

**Data Analysis**

Plantar pressure data were normalized for foot size and foot progression angle on the pressure plate according to the method developed by Keijzers et al. After normalization, the maximal peak pressure of each separate virtual sensor (pixel) was averaged over the five trials in each condition for each participant. To study the effect of an MP on plantar pressure, the differences between walking with and without an MP in peak pressure for each pixel underneath the whole foot were calculated for the total group.

The motion data were filtered using a second-order low-pass Butterworth filter with a cutoff frequency of 8 Hz and were subsequently normalized to 0% to 100% of the stance phase (from heel contact to toe-off). Heel contact was defined as the ground reaction force exceeding 20 N and toe-off as 20 N or less. After normalization, the data from the five trials in each condition were averaged for each participant.

The main outcome measure, forefoot width, was defined as the distance between the marker placed medially on the distal head of the first metatarsal bone and the marker placed laterally on the distal head of the fifth metatarsal bone. To demonstrate the effect of an MP on spreading of the forefoot, the mean width of the forefoot during the stance phase was compared between walking with and walking without an MP. Subsequently, the effect of MPs was studied during midstance (from one-third to two-thirds of the stance phase) because the largest effect of the MP was expected during this stage of the stance phase. In addition, the width between the bases of the first and fifth metatarsals was assessed. The mean height of the marker at the second metatarsophalangeal joint during midstance was determined to describe the effect of the MP on the second metatarsophalangeal joint. Walking speed was determined from the heel marker data of one stride of the contralateral foot in each trial.

**Statistical Analysis**

Paired samples *t* tests were used to test the difference in peak pressures between walking with and without an MP for each pixel with a peak pressure greater than 40 kPa (223 pixels). The significance level was corrected for the multiple comparisons using a Bonferroni correction (*P* < .000224). One-way repeated-measures analyses of variance (ANOVAS) with “condition” (with MP versus without MP) as the within-subjects factor and “group” (controls versus patients) as the between-subjects factor were used to test the differences due to MPs in forefoot width during the whole stance phase, forefoot width during midstance, height of the second metatarsophalangeal joint, and walking speed. To justify the use of these ANOVAs, we checked the normality of the data using Shapiro-Wilk tests. The Shapiro-Wilk tests revealed that all of the variables were normally distributed. The measured distances for the accuracy of the motion analysis system were compared using inde-
dependent Student $t$ tests. The significance level was set at $P < .05$.

**Results**

Considering the total group, the mean ± SD walking speed was not significantly different between walking with an MP (4.70 ± 0.40 km/h) and without an MP (4.75 ± 0.41 km/h) (ANOVA, $F_{1,26} = 2.18, P = .15$). Furthermore, no significant interaction was seen between condition and group ($F_{1,26} = 0.329, P = .57$). Controls had a slightly higher mean ± SD walking speed than did patients with metatarsalgia (4.89 ± 0.41 km/h versus 4.59 ± 0.35 km/h, $F_{1,26} = 4.28, P < .05$).

Peak plantar pressures decreased significantly under the metatarsal heads for walking with an MP (Fig. 2). For the total group, the pixel with the highest decrease revealed a mean ± SD decrease in peak pressure of 44 ± 39 kPa. In contrast, walking with an MP induced a mean ± SD increase of 124 ± 32 kPa in peak pressure for the pixel with the highest increase, just proximal to the metatarsal heads at the position of the MP.

The width of the foot during gait was evaluated using markers located at the distal heads of the first and fifth metatarsal bones (markers 3 and 4 in Fig. 1). The forefoot spread after heel contact, reached the maximum width during midstance, and finally decreased after the heel-off phase (Fig. 3). During the stance phase, participants in the control group showed a mean ± SD maximum increase in forefoot width of 8.3 ± 1.5 mm, whereas it was 8.5 ± 2.2 mm for patients with metatarsalgia. An MP resulted in significantly larger mean ± SD increases (0.60 ± 0.38 mm) in forefoot width in patients and controls ($F_{1,26} = 68.25, P < .001$) (Table 2). Only one of the 28 feet showed no increase in forefoot width as a result of the MP. There was no significant difference in forefoot width between controls and patients ($F_{1,26} = .23, P = .64$) and no significant interaction between condition and group ($F_{1,26} = 0.02, P = .88$). The increase in forefoot width during midstance was larger than the increase over the whole stance phase. The presence of an MP caused an additional increase in forefoot width during midstance.
significant mean ± SD increase of 0.74 ± 0.44 mm ($F_{1,26} = 77.25, P < .001$) during midstance. Again, the ANOVA revealed no significant difference between controls and patients ($F_{1,26} = 0.92, P = .35$) and no significant interaction effect ($F_{1,26} = 0.28, P = .60$). Similarly, only one of the 28 feet demonstrated a decrease in forefoot width during midstance. To rule out the possibility that the results were due to the MP being taped under the foot, we studied the effect of an MP on forefoot width in an unloaded condition in three healthy individuals. Two participants showed a small increase in forefoot width (0.01 and 0.10 mm) as a result of the MP, and one showed a decrease of 0.33 mm. These results indicate that in an unloaded situation, an MP does not affect forefoot width.

The radiographs revealed that an MP also increases the distance between the first and fifth metatarsal bones in this static measurement (Fig. 4). The measured forefoot width was 86.9, 86.9, and 87.1 mm without an MP and 87.4 mm on three occasions with an MP.

In addition to forefoot width at the metatarsal heads, we studied the width at the bases of the metatarsal bones (markers 5 and 6 in Fig. 1) during gait. A slightly smaller (mean ± SD: 0.45 ± 0.38 mm versus 0.60 ± 0.38 mm) but significant ($F_{1,23} = 33.72, P < .001$) increase was found for the width at the bases of the metatarsal bones when the increases with and without an MP were compared.

To evaluate the height of the foot, the height of the marker on the second metatarsophalangeal joint was used. The height showed a significant mean ± SD increase ($F_{1,26} = 27.71, P < .001$) of 0.62 ± 0.68 mm for walking with an MP (35.61 ± 2.44 mm) compared with walking without an MP (34.99 ± 2.43 mm). The ANOVA revealed no difference in the effect of an MP on the height of the marker on the metatarsophalangeal joint between controls and patients ($F_{1,26} = 1.84, P = .19$), and there was no significant interaction between condition and group ($F_{1,26} = 3.26, P = .08$).

Considering the accuracy of the motion analysis system, the comparisons where the distance increased 0.5 mm were shown to be significant ($t = 55.49, \text{mean} \pm \text{SD increase} = 0.53 \pm 0.43 \text{mm}, P < .001$ and $t = 57.85, \text{mean} \pm \text{SD increase} = 0.52 \pm 0.40 \text{mm}, P < .001$). Moreover, even the increases of 0.1 mm were significantly different from each other ($P < .001$ for all of the comparisons). These results indicate an accuracy of at least 0.1 mm.

**Discussion**

The results of this study indicate that the width of the forefoot increases during the stance phase of walking and that this increase is significantly larger when an MP is used. Although the extra increase

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**Table 2. Width of the Forefoot and Height of the Marker on the Second Metatarsal Joint**

<table>
<thead>
<tr>
<th></th>
<th>Without MP</th>
<th>With MP</th>
<th>Increase</th>
<th>Without MP</th>
<th>With MP</th>
<th>Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controls</td>
<td>107.02 ± 8.78</td>
<td>107.64 ± 8.76</td>
<td>0.62 ± 0.36</td>
<td>34.16 ± 2.23</td>
<td>35.04 ± 2.26</td>
<td>0.88 ± 0.94</td>
</tr>
<tr>
<td>Patients</td>
<td>105.69 ± 6.07</td>
<td>106.28 ± 6.06</td>
<td>0.60 ± 0.40</td>
<td>35.61 ± 2.46</td>
<td>36.04 ± 2.55</td>
<td>0.43 ± 0.29</td>
</tr>
<tr>
<td>Combined</td>
<td>106.26 ± 7.23</td>
<td>106.86 ± 7.22</td>
<td>0.60 ± 0.38</td>
<td>34.99 ± 2.43</td>
<td>35.61 ± 2.44</td>
<td>0.62 ± 0.68</td>
</tr>
</tbody>
</table>

Abbreviation: MP, metatarsal pad.

Note: Data are given as mean ± SD. Analyses of variance revealed significant increases in the height of the second metatarsal joint and a significant increase in the width of the forefoot for walking with versus without an MP. In addition, no significant differences between the two groups and no significant interactions were found.
with an MP was small (0.60 mm), the accuracy study revealed that the increase was at least greater than the accuracy of the measurement equipment. Moreover, the maximal extra increase of 0.74 mm during midstance is an increase of 9% of the increase of 8.4 mm in forefoot width during walking. Furthermore, the extra increase was significant and was seen in 27 of the 28 feet.

It could be argued that the results of the present study might be the result of skin movements. However, the metatarsal markers were placed at the outer rim of the foot at the beginning of the experiments. Therefore, any skin movement would have decreased the forefoot width. Moreover, the radiographs showed a comparable increase in width for the condition where the MP was present compared with the condition without an MP. Furthermore, several articles have shown that skin movements at the foot are relatively small compared with those on other parts of the lower body. A recent study confirmed that skin-mounted markers on the foot provide reliable data compared with bone-mounted markers. It follows that it is much more reasonable to assume that the widening of the forefoot is attributable to a mediolateral expansion of the foot. If such expansion were absent, one would expect that the measured distance between the markers would show a decrease when an MP was applied (the same mediolateral length of the foot but curved around the MP should lead to a smaller distance between the medial and lateral markers; Fig. 1 [hypothesis 1, fixed chain hypothesis]). This was not observed, however, and instead the distance increased systematically in almost all of the experiments. Hence, the present data are far more compatible with hypothesis 2, stating that the presence of an MP causes the foot to expand in the mediolateral direction. Such expansion is likely to be accompanied by an increase in the distance between the metatarsal bones, and this could be a factor involved in pain relief. In this respect, it is noteworthy that the increase in width at the distal heads is supported by a slightly smaller increase in width at the bases of the metatarsals.

It is clear that these remain indirect arguments and that further experiments are needed to confirm this hypothesis and to exclude alternative explanations. One possible alternative is that the pain relief is the result of the interaction between different types of afferents. The presence of an MP may provide extra stimulation of the foot sole, thereby providing a source of presynaptic inhibition of nociceptive afferents from the same region. To refute this possibility, it would be interesting to know whether the effect of an MP is less pronounced in patients with sensory neuropathy because the possible inhibition of the pain signal is disturbed in this population. To our knowledge, there is no study of pain reductions resulting from an MP in patients with sensory neuropathy.

In this context, the role of the exact location of the MP deserves some attention as well. The presently found significant increase in peak pressure at the position of the MP and, more important, a significant decrease just distal from the MP at the position of the distal metatarsal heads suggested that the MPs were placed at the most optimal...
position, as indicated by Hsi and colleagues. However, a recent study demonstrated that the exact positioning of the MP on the longitudinal axis was not as important as clinically presumed, and as suggested by Hsi et al., as long as the MP was placed proximal to the metatarsal heads. In the present study, the correct positioning of the MPs was demonstrated by the decreases in peak pressure under the second metatarsal heads. Compared with other studies where decreases in peak pressures of 12% to 15% were demonstrated, we found comparable decreases of 13% and 14% for patients with metatarsalgia and controls, respectively. A study by Hsi and colleagues showed a much larger decrease of 37%. However, in that study, severely affected patients with metatarsalgia were used and high mean SD peak pressures (687 ± 228 kPa) were found under the second metatarsal head for walking without an MP. Hence, a correctly placed MP will redistribute the plantar pressure from the second to fourth metatarsals to the area where the MP is placed.

In six participants in the control group and six patients, both feet were tested. The variance in the difference between left and right forefoot width (within participants) was larger than the variance between participants. Therefore, both feet of one subject could more or less be used as independent observations in this study.

In conclusion, an MP induces pressure reduction under the metatarsal heads and increased forefoot width during the whole stance phase of gait. In addition, an increase in the height of the second metatarsophalangeal joint was observed. We propose that the combination of these findings results in increased space between the metatarsals, which could be an underlying mechanism of an MP to reduce pain in patients with metatarsalgia.

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**Conflict of Interest:** None reported.

**References**