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An-Hsiung Chang
Medical College of Wisconsin

Ziad U. Abu-Faraj
Marquette University

Gerald F. Harris
Marquette University, gerald.harris@marquette.edu

Joe Nery
Medical College of Wisconsin

Michael J. Shereff
Medical College of Wisconsin

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An-Hsiung Chang
Department of Orthopaedic Surgery, Medical College of Wisconsin, Milwaukee, WI

Ziad U. Abu-Faraj

Department of Biomedical Engineering, Marquette University, Milwaukee, WI
Shriners Hospital for Crippled Children, Chicago Unit, Chicago, IL
Rehabilitation Medicine Service, Clement J. Zablocki VA Medical Center, Milwaukee, WI

Gerald F. Harris

Department of Orthopaedic Surgery, Medical College of Wisconsin, Milwaukee, WI
Department of Biomedical Engineering, Marquette University, Milwaukee, WI
Shriners Hospital for Crippled Children, Chicago Unit, Chicago, IL
Rehabilitation Medicine Service, Clement J. Zablocki VA Medical Center, Milwaukee, WI

Joey Nery

Department of Orthopaedic Surgery, Medical College of Wisconsin, Milwaukee, WI

Michael J. Shereff

Department of Orthopaedic Surgery, Medical College of Wisconsin, Milwaukee, WI

Abstract

Metatarsal pads are frequently prescribed for nonoperative management of metatarsalgia due to various etiologies. When appropriately placed, they are effective in reducing pressures under the metatarsal heads on the plantar surface of the foot. Despite the positive clinical reports that have been cited, there are no quantitative studies documenting the load redistribution effects of these pads during multiple step usage within the shoe environment. The objective of this study was to assess changes in plantar pressure metrics resulting from pad use. Ten normal adult male subjects were tested during a series of 400-step trials. Pressures were recorded from eight discrete plantar locations at the hindfoot, midfoot, and forefoot regions of the insole. Significant increases in peak pressures, contact durations, and pressure-time integrals were noted at the metatarsal shaft region with pad use ($P \leq .05$). Statistically significant changes in metric values were not seen at the other plantar locations, although metatarsal pad use resulted in mild decreases in mean peak pressures at the first and second metatarsal heads and slight increases laterally. Contact durations decreased at all metatarsal head locations, while pressure-time integrals decreased at the first, second, third, and fourth metatarsal heads. A slight increase in pressure-time integrals was seen at the fifth metatarsal head. The redistribution of plantar pressures tended to relate not only to the dimensions of the metatarsal pads, but also to foot size, anatomic foot configuration, and pad location. Knowledge of these parameters, along with careful control of pad dimensions and placement, allows use of the metatarsal pad as an effective orthotic device for redistributing forefoot plantar pressures.

INTRODUCTION

During stance phase, the foot provides weightbearing support, propulsive forces for locomotion, and shock absorption for distribution of impact forces.[13] As the final segment in the lower extremity linkage system, the foot must transmit the forces of stance and locomotion to the surrounding environment. To be effective, this transmission must be adapted to diversities in terrain while providing both stability and load distribution.[12] According to Menkveld et al.,[17] four functional tasks are accomplished by the foot during stance: acceptance of impact load at heel strike, terrain accommodation during weight acceptance, stability and load distribution during foot flat, and propulsion for forward progression

during push-off. A pathological foot is inevitably challenged in the performance of these functional tasks, with a resultant change in plantar load distribution. Focal areas of high pressure can develop that may affect stability and serve as sources of discomfort and pain.

Relief of pain and redistribution of plantar pressures are frequent goals of metatarsal pad use when treating patients with metatarsalgia.[2,3,10,14] Any abnormality that leads to increased loading of the metatarsal head will manifest itself as metatarsalgia.

Metatarsal pads are among the most frequently prescribed orthotic devices for nonoperative treatment of the foot and ankle.[3,10,14] Although they can be effective in rebalancing plantar loads, great care must be exercised to prevent excessive load transfer to neighboring areas of the foot.[2,15,19] The quantitative, multistep effects of metatarsal pad use upon plantar load redistribution have not been described. Characteristics of foot-to-ground contact forces and plantar pressure distribution have been studied by several inves-tigators.[1,2,4–11,17–20,22–30] Few, however, have quantitatively assessed multistep, in-shoe foot pressure distribution.[7,8,23–30] To be effective, discrete pressure transducers should not alter the natural gait of the subject. They should be thin and flexible, durable, and capable of withstanding repetitive gait cycles.[24]

In 1990, Schaff and Cavanagh[19] used an EMED pressure-measuring insole to examine the effects of rocker-bottom shoe modification on plantar pressures. The authors noted that certain regions of the foot could not be monitored with the insole used. Precisely, a band in the midfoot, the lateral aspects of the forefoot and toes, and medial aspects of the heel and hallux received less than complete coverage. It was also noted that estimated forces were subject to some inaccuracy due to the integration of residual noise in lightly loaded elements. In 1990, Holmes and Timmerman[10] studied the effects of metatarsal pads on plantar pressures in a group of 10 volunteers. Single-step data were acquired using a pedobarograph mounted within the gait walkway during 15 trials per subject. Subjects were barefoot; the pad was placed directly on the foot just proximal to the metatarsal pressure areas (shoes were not worn). During clinical application, the metatarsal pad is usually affixed to the insole within the shoe. This does not restrict relative motion of the forefoot during weightbearing and swing phases of gait.[21] In 1992, Guirini et al.[6] reported on an analysis of felted-foam dressings for management of diabetic foot ulcerations. The felted-foam dressing was reported to be effective in relieving pressures, although ulcer location varied. The possible adverse effects of pressure redistribution in insensate feet were not described. This group used an F-Scan (Tekscan, Boston, MA) system that utilized a thin sheet of 960 resistive insole sensors attached to an umbilical in the laboratory. The F-Scan insole is usage-limited and methods for calibration that compensate for nonlinearity, bending, wear, and temperature drift are not described.[24,26]

In this study, Interlink (Santa Barbara, CA) pressure sensors were used with a portable in-shoe data acquisition system to acquire multistep pressure data. The microprocessor-based system has been used in previous studies of walking and shuffling gait, plantar asymmetry, cadence, and assistive device use.[8,23–30]

MATERIALS AND METHODS

A third generation, custom-made, portable, in-shoe, microprocessor-based data acquisition system was used to record pressure data from eight discrete plantar locations[8,23–30] The system allows long-term continuous recording (up to 2 hr at 40 Hz) of plantar pressures from up to 14 sensor locations. The

system utilizes a Dallas Semiconductor (Dallas, TX) microprocessor (DS5001FP-16) and is powered by five AA Ni-Cad batteries. The unit is mounted in a 21 × 12 × 3 cm box and weighs 340 g. Subjects carry the unit during free ambulation in a small beltpack. Plantar pressure data are uploaded into a personal computer for further processing, analysis, and display.

Interlink conductive polymer pressure sensors (1.5 cm in diameter, 0.25 mm thick) were used with the system to record plantar pressures. These sensors offer the advantages of flexibility, durability, reliability, overload tolerance, electronic simplicity, and low cost (< $4 each).[8,16,23–30] With increasing pressure, the conductive polymer sensors provide a logarithmic resistance drop that is converted into a pressure decrement by the microprocessor system. Quantitative sensor characteristics (hysteresis, nonrepeatability, nonlinearity, sensitivity and temperature drift, etc.) are described elsewhere.[16,24,26,27,29]

For sensor calibration, a dynamic force application unit consisting of a compression lever, 440 N load cell, and preamplifier was used. Dynamic loads with durations similar to that of stance phase were applied to each sensor during calibration. Calibration data were then automatically loaded to the personal computer, where a look-up table was generated for each sensor. A metal disk (1.8 cm in diameter, 1 mm thick) was attached to the back of each sensor to keep it flat and prevent excessive hysteresis due to bending.

Sensors were mounted into insoles (6.4 mm thick) composed of a top layer of Plastazote™ (Bakelite Xylonite Ltd, London, England) and a lower layer of cork. The upper layer was sculpted to accept the sensors and thin metal backings that were mounted flush with the top surface.[24,29,30] The eight sensor locations were determined through clinical examination and recorded foot impressions from an Apex foot imprinter (Hackensack, NJ) during three successive barefoot trials. Because the hallux frequently extended medially beyond the insole margin, the hallux (Hx) sensor was positioned by rotating the recorded contact point laterally about an arc centered at the first metatarsophalangeal joint. This simulated hallux compression by the inner medial wall of the shoe. A medial longitudinal arch sensor (MLA) was placed medially near the insole edge and longitudinally at the center of the arch hollow. A single sensor was located between the third and fourth metatarsal heads (3&4M) to accommodate variations in proximity and size.[10] The other sensors were located under the calcaneal tuberosity (H), midpoint of the metatarsal shaft region corresponding with the apex of the metatarsal pad (MSR), head of the first metatarsal (1M), head of the second metatarsal (2M), and head of the fifth metatarsal (5M) (Fig. 1).
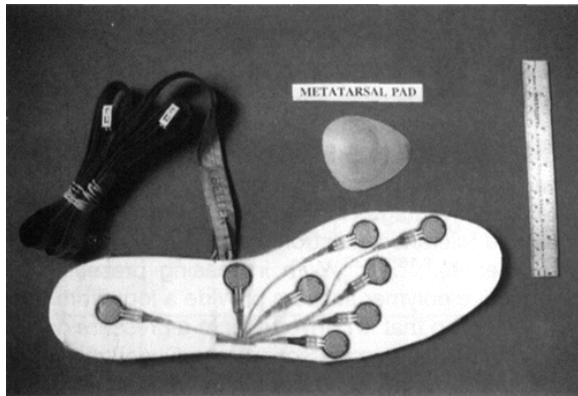
Fig. 1. A metatarsal pad and an instrumented insole with eight discrete pressure sensors located at the calcaneus, medial longitudinal arch, metatarsal shaft region, first metatarsal head, second metatarsal head, third and fourth metatarsal heads, fifth metatarsal head, and hallux.

The metatarsal pads used for the study were made of a rubber material with maximum linear dimensions of 6 cm (length) × 5.2 cm (width) × 0.8 cm (thickness). The pads included an adhesive backing that facilitated attachment and restricted motion during the subject tests. The pads were adhered to the base of the insoles and positioned such that the longitudinal (length) axis overlapped with that of the heel oval as defined by the foot imprint data. The distal pad margins were separated by at least 5 mm from the metatarsal heads. An insole and pad without sensors were used simultaneously on the contralateral foot to provide a balanced gait pattern during subject testing. The instrumented insole and metatarsal pad were inserted in P.W. Minor Extra Depth® Easy Sport athletic shoes (Batavia, NY).

Ten male rearfoot strikers, as determined by measurement of stresses beneath the calcaneus and other plantar surfaces with the insole system, were selected for the study.[4,5] Subjects ranged in age from 25 to 38 years (mean ± SD = 29 ± 4 years) and had a mean height of 179 ± 7 cm and mean weight of 80 ± 13 kg. The mean shoe size of the adult males tested was U.S. men's size 9 $1/2$ ± 1. None of the subjects suffered from foot disorders or gross abnormality.

Subjects were asked to walk at their own natural cadence on an 80-meter concrete walkway.[9] Acclimation to the experimental shoes and establishment of a constant temperature (shoe) environment was provided during a 5-min pretest period.[4,5,24] Two data-gathering sessions (400 steps each) were then conducted. During the first session, subjects were tested without the use of metatarsal pads. This was followed by a 10-min rest period and then a second session in which the pads were used. Steps around the ends of the walkway were excluded to eliminate any altered gait patterns during the turn maneuver. Peak plantar pressures, pressure-time integrals and contact durations were determined for each of the insole sensors during the multistep trials (Fig. 2).
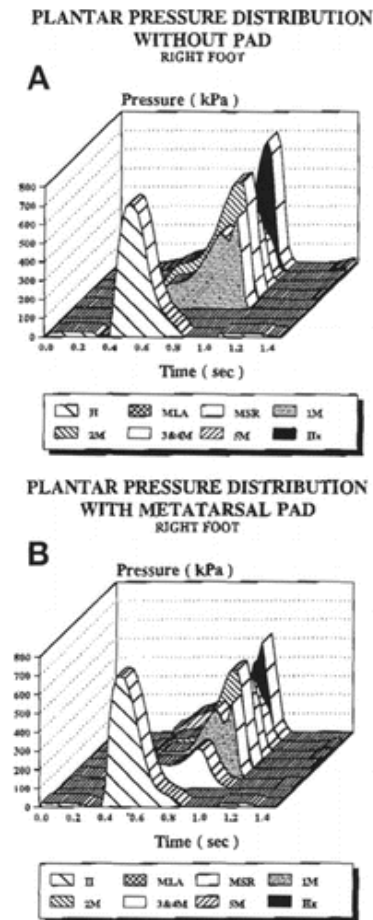
Fig. 2. Plantar pressure distribution for a typical subject *(A)* without and (*B*) with a metatarsal pad.

The average walking speed of the subjects tested was 1.6 ± 0.1 meters/sec, both without and with metatarsal pad use. The mean stride length was 1.7 ± 0.1 meters, and the average number of steps per trial was 369 ± 17 steps, again both without and with the metatarsal pad. Subjects did not report any discomfort or fatigue during the test trials.

RESULTS

Metric values for a typical subject tested with and without the use of a metatarsal pad are shown in Figure 3. Mean and standard deviation values at each sensor location are provided for peak pressures, contact durations, and pressure-time integrals. Without the use of the metatarsal pad, MLA and MSR sensors registered zero pressure values. For this subject, use of the metatarsal pad resulted in discernible increases in all metric values at the MSR sensor, but no discernible changes at the MLA sensor. Metatarsal pad use resulted in peak load increases in the midfoot region and peak load decreases in the forefoot region and at the calcaneus.
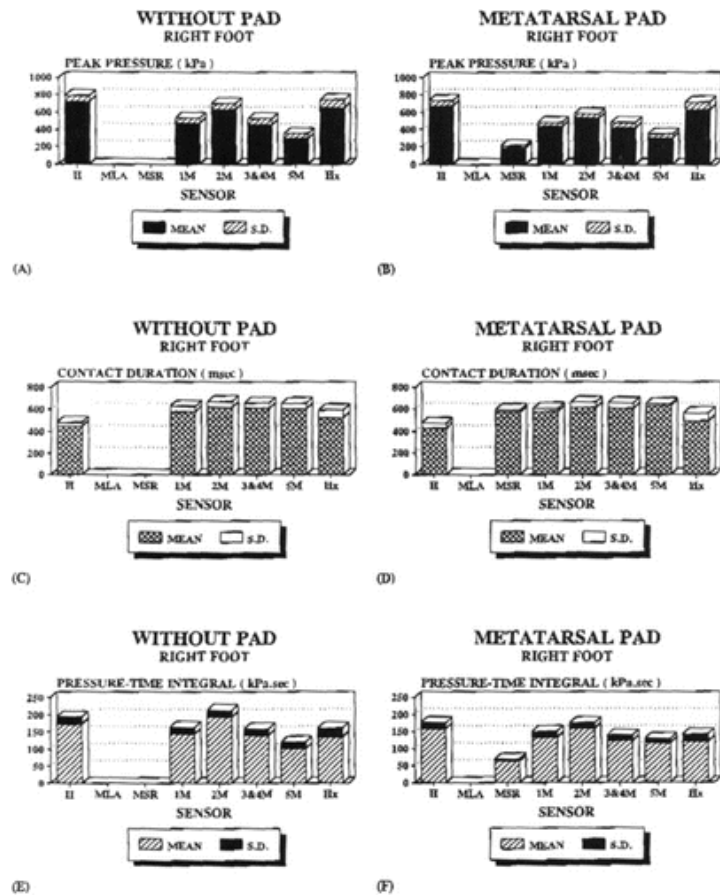
Fig. 3. Foot pressure distribution pattern by sensor in a typical subject: peak pressure *(A)* without and (*B*) with a metatarsal pad; contact duration (*C*) without and (*D*) with a metatarsal pad; and pressure-time integral (*E*) without and (*F)* with a metatarsal pad.

Results for the total subject population with and without pad use are presented in Table 1. The mean and standard deviation values for peak pressures (kPa), contact durations (msec) and pressure-time integrals (kPa.sec) are provided by sensor location (Table 1). Without pad use, the lowest metric values were consistently seen at the MLA and MSR sensors. The highest values were noted at the H and Hx sensors for peak pressures, at the 3&4M and 5M sensors for contact durations, and at the H and 1M sensors for pressure-time integrals. With pad use, the lowest metric values consistently occurred at the medial longitudinal arch (MLA) region. The greatest values were seen at the H and Hx sensors for peak pressures, at the 3&4M and 5M sensors for contact durations, and at the H and 1M sensors for pressure-time integrals.

**TABLE 1** Plantar Pressure Distribution Without and With Metatarsal Pad Use

Sensor location	Peak pressure (kPa)	Contact duration (msec)	Pressure-time integral (kPa-sec)
Without pad use			
Calcaneus	567.6 ± 182.5	412.0 ± 65.0	127.6 ± 42.9
Medial longitudinal arch	0.6 ± 4.9	6.0 ± 49.0	0.1 ± 0.9
Metatarsal shaft region	11.7 ± 23.5	82.0 ± 169.0	2.4 ± 4.8
1st metatarsal head	527.1 ± 210.3	506.0 ± 76.0	132.3 ± 53.1
2nd metatarsal head	469.3 ± 129.5	520.0 ± 72.0	120.8 ± 44.1
3rd & 4th metatarsal heads	392.2 ± 113.2	592.0 ± 62.0	112.9 ± 26.5
5th metatarsal head	271.6 ± 101.3	642.0 ± 333.0	94.1 ± 40.3
Hallux	606.6 ± 218.3	430.0 ± 102.0	110.9 ± 46.5
With pad use			
Calcaneus	614.3 ± 192.4	397.0 ± 70.0	134.7 ± 48.3
Medial longitudinal arch	0.0 ± 0.7	14.0 ± 6.0	0.0 ± 0.10
Metatarsal shaft region	138.7 ± 93.6	450.0 ± 169.0	40.1 ± 29.3
1st metatarsal head	504.6 ± 197.0	502.0 ± 91.0	124.9 ± 49.9
2nd metatarsal head	455.9 ± 110.5	500.0 ± 102.0	112.4 ± 41.7
3rd & 4th metatarsal heads	404.4 ± 138.2	584.0 ± 72.0	109.5 ± 30.4
5th metatarsal head	281.3 ± 109.8	609.0 ± 105.0	94.8 ± 36.3
Hallux	559.4 ± 162.0	433.0 ± 118.0	102.7 ± 39.1

The MLA sensor was positioned so that it might detect possible increases in plantar pressure under the medial longitudinal arch, but none was seen.
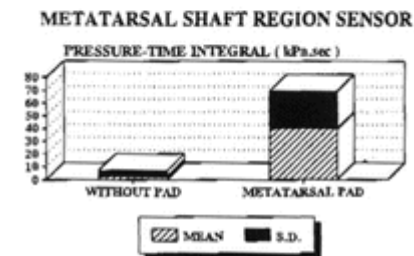
Alterations in metric values at the MSR sensor are shown in Figure 4 for the test group. The increases in peak pressure, contact duration, and pressure-time integral values following application of the metatarsal pad were statistically significant $(P \leq .05)$. Peak pressures increased from 11.7 to 138.7 kPa, contact durations increased from 82.0 to 450.0 msec, and pressure-time integrals increased from 2.4 to 40.1 kPa.sec. Statistically significant changes in metric values were not seen at the other plantar locations, although metatarsal pad use resulted in mild decreases in mean peak pressures at the first and second metatarsal heads and slight increases laterally. Contact durations decreased at all metatarsal head locations, while pressure-time integrals decreased at the first, second, third, and fourth metatarsal heads. A slight increase in pressure-time integrals was seen at the fifth metatarsal head.
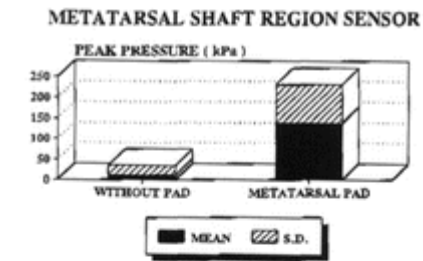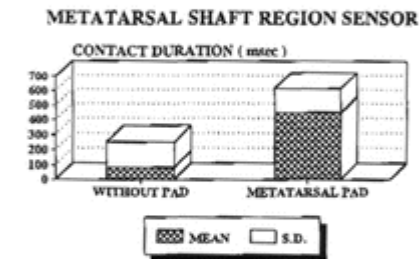
Fig. 4. Alterations in metric values at the metatarsal shaft region sensor for the test group: (*A*) peak pressure, (*B*) contact duration, and (*C*) pressure-time integral.

DISCUSSION

It has been reasoned that decreasing the forces transmitted to the metatarsal prominences (peripheral pad areas) is effective in reducing metatarsalgia pain. Metatarsal pads have been considered as one modality of therapy when other mechanical alterations are suspected of causing metatarsal pain.[10]

In the group of subjects studied in this work, the most significant changes in pressure metrics were noted with pad use in the midfoot (MSR) area *(P ≤ .05)*. Peak pressures increased from 11.7 to 138.7 kPa, contact durations increased from 82.0 to 450.0 msec, and pressure-time integrals increased from 2.4 to 40.1 kPa.sec. This pressure redistribution was characterized by increased peak loads delivered to the normally unloaded MSR area and decreased peak loads delivered to the more peripheral areas.

Statistically significant changes in metric values were not seen at the other plantar locations, although metatarsal pad use resulted in mild decreases in peak pressures at the first and second metatarsal heads and at the hallux and slight increases laterally and at the calcaneus. The largest increase in mean peak plantar pressures occurred at the calcaneus and measured 8.2%. Other increases in mean peak pressures occurred at the third, fourth, and fifth metatarsal heads. The largest decrease in mean peak

plantar pressures occurred at the hallux and measured 7.8%. Other decreases in mean peak plantar pressures occurred at the first and second metatarsal heads, with a 4.3% decrease at 1M and a 2.9% decrease at 2M. Alterations in peak pressures in these studies are consistent with the findings in the studies by Holmes and Timmerman,[10,11] in which subjects demonstrated differing outcomes with metatarsal pad use.

Contact durations with metatarsal pad use did not follow the same trends as the peak pressures. Rather, the contact durations decreased at all metatarsal head locations (1M, 2M, 3&4M, and 5M) as well as at the calcaneus with metatarsal pad usage. Contact durations increased at the hallux.

Variations in pressure-time integrals with metatarsal pad use were slightly different from those obtained for the peak pressures. Increases in pressure-time integral values were seen at the calcaneus, while decreases were noted at the forefoot region of the insole. The largest decreases in pressure-time integrals occurred at the hallux and at the second metatarsal head. Further decreases in pressure-time integrals occurred at the first, third, and fourth metatarsal heads.

The results from this study tend to indicate that a metatarsal pad should be positioned at the center of the central rays and just proximal to the metatarsal heads. The optimal location seems to be within the margins defined by the medial border of the second metatarsal shaft and the lateral border of the fourth metatarsal shaft. Further quantitative studies should address these issues as they relate to relative foot size and pad geometry.

Metatarsal pad use resulted in mild decreases in mean peak pressures at the first and second metatarsal heads and slight increases laterally. Contact durations decreased at all metatarsal head locations, while pressure-time integrals decreased at the first, second, third, and fourth metatarsal heads. This redistribution in pressure metrics came at a cost of a significant increase in pressure in the metatarsal shaft region ($P \leq .05$).

Acknowledgements

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