Applied Ergonomics 46 (2015) 84–90

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

# Time to onset of pain: Effects of magnitude and location for static pressures applied to the plantar foot

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ARTICLE INFO

*Article history:*
Received 21 December 2013
Accepted 12 July 2014
Available online 10 August 2014

*Keywords:*
Standing
Pain-pressure threshold
Sensory testing

ABSTRACT

Mechanisms that cause foot discomfort during prolonged standing are poorly understood. There is currently no method for evaluating discomfort associated with low levels of static pressure that are typical during standing. Pain thresholds were measured for 20 healthy participants by applying five levels of static pressure at different plantar foot locations. A survival analysis was performed to determine the effects of pressure magnitude and foot location on the time until pain onset. Time to pain onset was significantly affected by pressure magnitude ($P < 0.001$); time decreased as pressure increased. Foot location was also significant ($P < 0.001$); greatest times to pain onset (least sensitive) were observed under the heel and fifth metatarsal head, shortest times (most sensitive) were found under the midfoot. This research presents a novel methodology for evaluating static pressure that may be applicable to product design.



## 1. Introduction

Prolonged standing is a daily requirement for many workers (Tissot et al., 2005) and has been linked to discomfort and fatigue in the lower limbs (e.g., Cham and Redfern, 2001; Madeleine et al., 1998). Shoe inserts have been shown to effectively mitigate discomfort (Cham and Redfern, 2001; King, 2002), but there is no agreement on which designs of footwear and shoe inserts are most effective. In order to select footwear and inserts that enhance comfort during standing, a better understanding is needed of the mechanisms that cause discomfort.

Suspected mechanisms for discomfort during standing include fatigue of leg and lower back muscles (Cook et al., 1993; Kim et al., 1994) and pooling of blood in the legs (Kraemer et al., 2000). However, the current study focused on localized pressure on the plantar (bottom) surface of the foot as a possible mechanism for discomfort during standing.

There is substantial physiological evidence suggesting that plantar pressure plays a role in the development of discomfort during prolonged standing. Plantar pressure causes compression of muscles, nerves, and bones in the foot, and high plantar pressures have been linked to foot pain and discomfort (Godfrey et al., 1967; Silvino et al., 1980). During static, barefoot standing, plantar pressures on the foot average about 70 kPa, with peaks of around 140–175 kPa (Cavanagh et al., 1987; Wiggermann and Keyserling, 2010) which far exceed pressures shown to cause skin, muscle, and nerve damage. Sustained pressures greater than 4–4.7 kPa exceed capillary pressure and put tissue at risk for ischemia (Kosiak et al., 1958; Dinsdale, 1974), and have been shown to cause nerve impairment in rabbits (Rydevik et al., 1981). Extended exposure to pressure above 15–20 kPa interrupts arterial blood flow and causes cell death in canines (Hargens et al., 1981). Although the sustained pressures tested in these laboratory and animal studies do not represent the cycles of loading and unloading that occur during prolonged standing, the high plantar pressures associated with standing as compared to the relatively low pressures that cause tissue damage suggests that plantar pressure that occurs during prolonged standing may play a role in discomfort.

Very little research has investigated the relationship between plantar foot pressure and discomfort (Rolke et al., 2005). The most common method for relating pain and pressure is the pain-pressure threshold (PPT), or the pressure at which pain is reported when a probe is pressed against the skin at a steadily increasing rate (Fransson-Hall and Kilbom, 1993). PPT has been studied in the second toe (Brennum et al., 1989) and the abductor hallucis of the arch of the foot (Rolke et al., 2005), but the only study to evaluate the PPT at multiple locations on the foot was Messing and Kilbom (2001) who found higher PPTs at the heel, and lower PPTs at the midfoot (i.e., the midfoot was more sensitive to pressure than the heel).

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http://dx.doi.org/10.1016/j.apergo.2014.07.008
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Although these PPT results may provide rudimentary information regarding the sensitivity of different foot locations to pain, the conditions of the PPT test are very dissimilar to the conditions of standing. Messing and Kilbom (2001) found mean PPT values of 550 kPa in the heel, which is nearly four times greater than peak pressures commonly observed during standing (Cavanagh et al., 1987). The steadily-increasing pressure applied in PPT tests is also not representative of the relatively static pressures associated with standing. The rate at which pressure is increased in a PPT test affects pressure threshold, with faster rates resulting in higher PPTs (Jensen et al., 1986). PPT tests do not provide information about how discomfort develops over time when the foot is exposed to low levels of static pressure associated with standing.

There is currently no test for measuring the effect of static pressure on discomfort in the foot. Because an increasing pressure is applied during the PPT test and the pressure corresponding to the onset of pain is the outcome measurement, PPT is incapable of testing static pressures. For a test to evaluate the effect of a given level of static pressure on discomfort, the *time* until the onset of pain is the necessary outcome measurement. Such a test would make it possible to evaluate the effects of relatively low pressures common during standing, and would also eliminate an inherent bias of a PPT test resulting from the rate at which pressure is increased.

The study presented herein introduces a test that measures the time to pain onset (TPO) under a static localized pressure. This test was used to investigate the effect of plantar pressure on this pain threshold for various levels of pressure to the heel and metatarsal heads that are common during standing. It was hypothesized that 1) TPO decreases as the magnitude of static pressure is increased, and 2) that foot locations superficial to soft tissue such as the midfoot are more sensitive to pressure than those superficial to bone such as the heel and metatarsal heads. A secondary objective of this study was to investigate the development of pain during standing by testing whether pressure can be used to predict the location of the onset of pain, and whether surface hardness affects pain onset.

## 2. Methods

This research was comprised of two experiments. The primary experiment consisted of a pain-pressure threshold test in which static pressures were applied to the foot and the time until the onset of pain was measured. A supplemental experiment was performed in which the time and location of the pain onset were recorded while participants stood on surfaces of different hardness.

### 2.1. Participants

20 healthy participants (10 male, 10 female) with no history of lower extremity disorders or chronic foot pain were recruited from a university student population. The mean age of participants was 21.2 years (SD, 2.5 years), and mean body mass was 70.0 kg (SD, 10.3 kg). To ensure that foot geometry (e.g., underlying bone location, size, and curvature) was relatively consistent with respect to the size of the probe that applied the pressure, only participants with a US shoe size of 8–9 (men) and the equivalent 9–10 (women) were eligible for the study. This size range was chosen to allow for recruitment of both the male and female population. Shoe sizes were measured using a Brannock Device® (The Brannock Device Co.; Liverpool, NY, USA). All participants provided written informed consent, and methods were approved by the university's Institutional Review Board.

### 2.2. Experiment 1: time to pain onset (TPO) under static localized pressure

The TPO test differed from previous PPT tests in that lower pressure levels were used and pressure remained constant. The time corresponding to the onset of pain was measured rather than the pressure corresponding to the onset of pain as in traditional PPT tests.

The TPO test was a full-factorial experiment with partial replication. The time until the onset of pain was measured for five constant levels of pressure (98, 147, 221, 294, and 392 kPa) at each of five plantar foot locations (heel, midfoot, base of the fifth metatarsal, and heads of the first and fifth metatarsals). These levels were chosen because they included pressure levels that were common during standing and because they demonstrated a range of TPO in pilot testing. One pressure level was replicated, so there were 30 total trials ($5 + 1$ pressure levels $\times$ 5 locations). The test locations at the heel and metatarsals were identified by palpating the bone and marking the center of the bony prominence. The midfoot location was identified by marking a point 6 cm from the heel along a line between the heel location and second metatarsal head. Fig. 2.1 illustrates the test locations.

During TPO trials, participants sat with the foot resting on a flat padded surface into which a small hole was cut. Underneath the surface, a digital video camera was pointed at the hole to consistently locate the testing site. To keep the foot in place, a padded restraint was adjusted to the dorsal aspect of the foot. A circular, 1 $cm^2$ probe with a flat neoprene rubber tip (Fransson-Hall and Kilbom, 1993) moved vertically through the hole to apply the pressure to the foot. The probe tip was model FD/RT, manufactured by Wagner Instruments (Greenwich, CT, USA). The probe was coupled with a lever, and the force applied to the foot was controlled by hanging a weight at various distances from the fulcrum of the lever. At the start of each trial, pressure was increased to the designated level over a 3-s interval. When participants reached the threshold of pain, they pulled a rope attached to the lever that retracted the probe. A load cell and linear potentiometer were used to measure the force and displacement of the probe during each trial. The TPO was determined from the load cell recordings by measuring the time between the moment the foot was fully loaded at the designated pressure and the moment the rope was pulled. If the participant did not pull the rope within 180 s, the trial was ended. Pilot testing showed that when pain was not reached within the first 180 s, the sensation of pain could take a

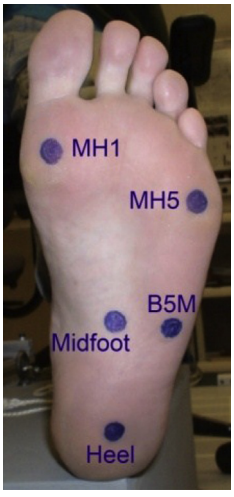


**Fig. 2.1.** Test locations on the foot for the TPO test.

very long time to develop and was difficult to identify as a discrete moment in time. To allow for potential comparisons to other established measures of discomfort, immediately after each trial participants reported their discomfort at the testing location on a visual analog scale, or VAS (Capodaglio, 2001).

The following instructions were read to each participant:

> "*When you are ready, I will press a probe against your foot. When you first sense a pinching, dull, or even itching sensation that you would characterize as pain, please pull the rope which removes the probe. Please note that we do not want to measure how much pain you can TOLERATE, just the moment that you first sense pain. Please be mindful of the sensation you consider pain, and try to respond when you reach this same feeling across all experimental trials.*"

Following these instructions, at least two practice trials were performed to familiarize the participant with the protocol and allow him/her to internally define their threshold of pain. Because significant PPT differences were not found between right and left locations on the arms, legs, hands, and feet (Rolke et al., 2005), TPO measurements were made on both the left and right foot to allow recovery time for tissue between pressure applications. The five locations were tested on one foot in a random order for a single level before moving to the opposite foot to test five locations in a random order at the next level. Alternating between the feet continued until all 30 trials were complete. The level of pressure was partially randomized, with higher levels of pressure being gradually introduced as the experiment progressed. Each pressure level was tested randomly within the following range of trials: pressure level 1, trials 1–10; level 2, trials 1–15; level 3, trials 5–20; level 4, trials 10–30; level 5, trials 15–30. This was necessary because pilot testing showed that when participants were exposed to high levels of pressure early in the experiment, they set very high definitions of pain pressure threshold. Only one pressure level was replicated to limit the length of the experiment out of concern that subjects could lose concentration and that repeated stress on foot tissue could cause a change in sensation. The pressure level to be replicated was not determined *a priori* but was instead selected independently for each participant during the experiment to prevent replicating either censored data (where pain was not reached within 180 s), or observations in which the participant immediately indicated pain. The level replicated was the lowest level for which TPO was uncensored for at least four of the foot locations. Pilot testing revealed that the lowest level where TPO were uncensored had the most variability. Replicating only this level increased the statistical confidence of the TPO estimates without needlessly lengthening the experiment (i.e., replicating censored trials or trials where the pain developed immediately).

A survival analysis (Kaplan and Meier, 1958) was performed using the LIFETEST procedure in SAS, version 9.2 (SAS Institute, Cary, NC, USA) to test for the effect of foot location and pressure level on time until the onset of pain. The replicated trials were evaluated using a repeated measures ANOVA to test whether trials performed later in the experimental session differed from trials testing the same conditions earlier in the session. A repeated measures ANOVA was also performed to test whether discomfort ratings were influenced by pressure level and foot location.

### 2.3. Experiment 2: standing pain threshold

Fifteen of the participants volunteered to take part in a standing pain threshold test. In this portion of the experiment, participants stood with their feet stationary on two surfaces of different hardness until they reached the threshold of pain in either of the two feet. The surfaces used were a compliant 4.4 cm-thick slow-recovery polyurethane memory foam ("soft"), a moderately hard 0.48 cm-thick firm ECH foam rubber ("medium"), and a hard acrylic plastic ("hard"). Two conditions were tested, a soft-medium comparison and medium-hard comparison for which each foot was positioned on a different surface. The experiment was a full-factorial randomized design, with each comparison tested twice so that every surface was experienced by both the left and right feet.

The height of the surfaces was adjusted for each participant such that they were perceived to be at the same level. The test surfaces rested on each of two force plates (model CR6-5-1; AMTI; Newton, MA, USA) which were used to provide visual feedback to help the participant maintain an even balance of weight between feet. Participants were instructed to keep their feet planted throughout the trial, and to indicate the location where they first sensed pain using the diagram shown in Fig. 2.2. The same definition of pain was used as for the TPO test. F-Scan® pressure sensors (Tekscan; Boston, MA, USA) were taped to the feet to record pressure while standing. These insoles are composed of a grid of 0.51 cm × 0.51 cm sensor elements that measure pressure by electrical resistance. Peak pressure for each standing trial was defined as the mean pressure value for the four adjacent sensor elements with the greatest combined pressure.

Chi-square tests were performed to test whether the origin of pain and peak pressure were uniformly distributed across regions of the foot (heel, midfoot, and forefoot). A chi-square test was also performed to test whether the peak pressure occurred in each foot region with the same frequency as the pain origin.

## 3. Results

### 3.1. Experiment 1: time to pain onset (TPO) under static localized pressure

The TPO was significantly affected by both pressure level ($P < 0.001$) and foot location ($P < 0.001$). Time decreased as pressure level increased, with all pressure levels significantly ($P < 0.05$) different from one another. Fig. 3.1 shows "survival curves" for each pressure level.

Time to pain onset was significantly earlier for the midfoot than for the other foot locations ($P < 0.001$), and the first metatarsal head also had significantly earlier pain onset time than the heel or fifth metatarsal head ($P < 0.05$). Figs. 3.2–3.4 show survival curves for each foot location at selected pressure levels. Fig. 3.2 shows that at

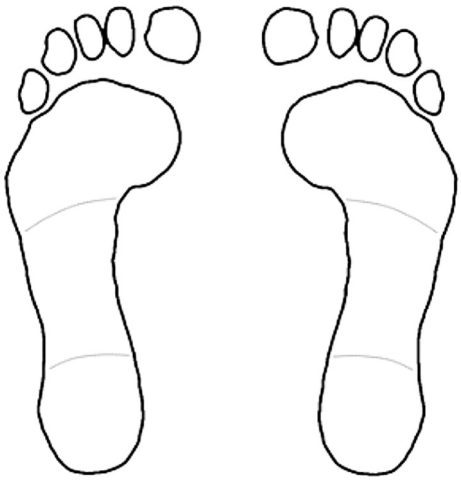

**Fig. 2.2.** Diagram used by the participants to indicate the location of the onset of pain when standing.

the lowest pressure level (98 kPa), most of the participants had not reached pain after 180 s in nearly all foot locations except in the midfoot, where 50% had reported pain after about 70 s Fig. 3.3 illustrates that at the third pressure level (221 kPa), the fifth metatarsal was least sensitive to pressure, with 50% reporting pain after approximately 120 s. Again, the midfoot was most sensitive to pressure, with 50% having reported pain after 50 s, and no participants lasting longer than 120 s. At the greatest pressure level (392 kPa) shown in Fig. 3.4, more than 50% of the participants reported pain after 30 s for all locations, and more than 75% reported pain after 70 s. Again, the midfoot was most sensitive to pressure, with all participants reporting pain after 20 s of applied pressure.

The ANOVA for the effect of replication showed that trials performed earlier in the experimental session did not have significantly different pain onset times than replications performed later in the session. However, this analysis can only be considered a rough estimation, because some trials (29 of 192 observations from both the first and second replications) were ended at the predetermined cutoff of 180 s, because the subject did not reach the threshold of pain.

Post-trial discomfort ratings measured on a visual analog scale (VAS) were significantly affected by both pressure level and foot location ($P < 0.001$). In pairwise comparisons, the discomfort ratings at each pressure level were significantly different from the other levels ($P < 0.05$), showing a consistent increase as pressure increased. The midfoot location had significantly higher discomfort ratings than all other foot locations ($P < 0.001$).

### 3.2. Experiment 2: standing pain threshold location

For the standing trials, the chi-square tests were significant, demonstrating that peak pressure ($P < 0.001$) and pain onset ($P < 0.001$) were not uniformly distributed on the foot during standing. Peak pressures (measured with the F-scan) were found at the heel in 78% of trials and at the metatarsal heads in 15% of trials (see Fig. 3.5). In comparison, pain onset was identified at the heel in 47% of trials, and at the metatarsal heads in 52% of trials (see Fig. 3.6). A chi-square test showed that the origin of pain did not occur at the same foot location with the same frequency as the peak pressure ($P < 0.001$). However, pain onset and peak pressure were co-located in 58% of trials.

Peak plantar pressures were significantly affected by flooring surface ($P < 0.001$). Each surface was significantly different from the others in pairwise comparisons, with the lowest peak pressure observed on the soft surface, and the highest peak pressure on the hard surface. When standing with the two feet on surfaces of different hardness, the onset of pain was generally located in the foot standing on the harder surface. When comparing the hard and medium surfaces, pain originated in the foot on the hard surface in 22 of 30 trials (73%). For the soft and medium surface comparison, pain originated in the foot on the medium surface in 25 of 30 trials (83%).

## 4. Discussion

This study was the first to evaluate the relationship between the time to onset of pain and levels of pressure on the plantar foot that commonly occur during standing. When considering the effect of foot location on pain threshold in the TPO test, our findings are generally consistent with Messing and Kilbom (2001) who found the lowest threshold for pain at the midfoot. However, Messing found the heel to have higher thresholds than all other locations, whereas our study identified the highest thresholds in both the heel and fifth metatarsal head. There are several possible physiological explanations for why pain threshold is higher in the heel

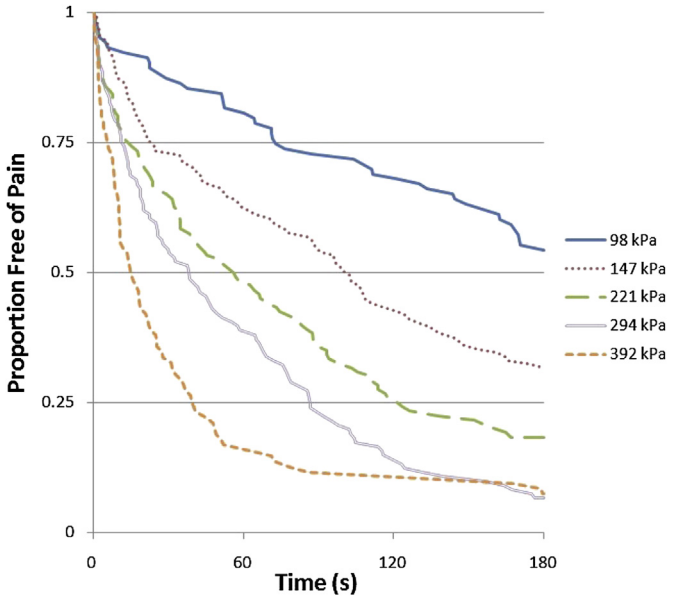


**Fig. 3.1.** Survival curves for all trials at each pressure level. The curves show the proportion of the participants not reporting pain versus time.

and metatarsal heads. In healthy subjects, these areas have the thickest fat pad (Klenerman, 1991), which may reduce pain threshold by distributing high localized pressures applied at the surface of the skin. These areas also have more callous formation that is more resistant to deformation, which in turn inhibits activation of cutaneous mechanoreceptors (Eyzaguirre and Findone, 1975). Finally, the medial plantar and lateral plantar nerves run through the midfoot, and it has been shown that pressure sensitivity is greater at locations over nervous tissue (Kosek et al., 1993).

Despite instructions to identify the onset of pain as the same sensation across all trials, the discomfort ratings reported by subjects using VAS after each trial increased with pressure level and were higher for the midfoot. A possible explanation for this result is

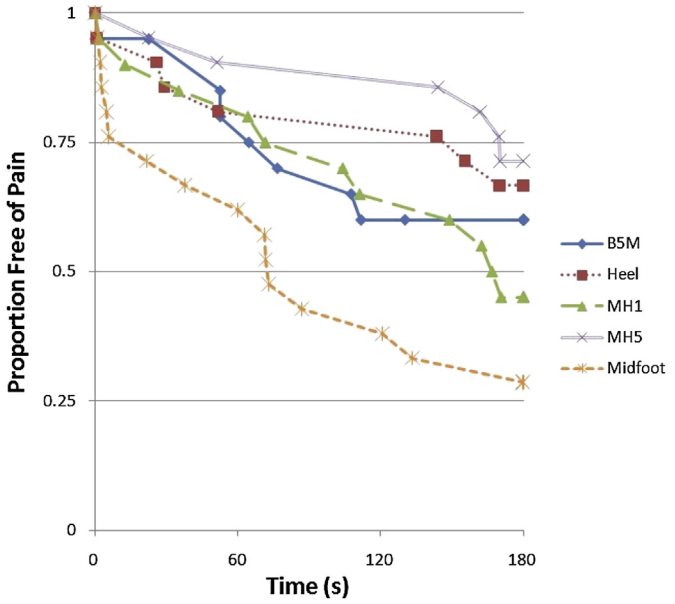


**Fig. 3.2.** Survival curves at pressure level 1 (98 kPa) for all tested foot locations. Note that the midfoot is more sensitive than other locations.

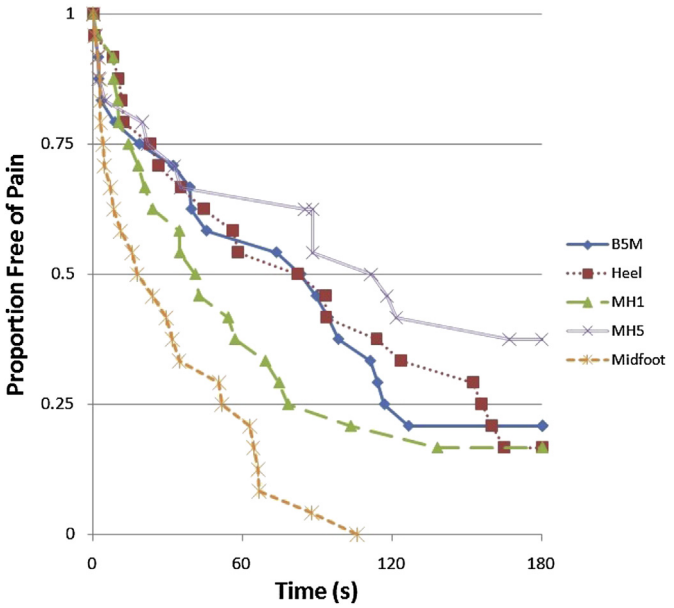


**Fig. 3.3.** Survival curves at pressure level 3 (221 kPa) for all tested foot locations. Slopes are substantially steeper than observed for pressure level 1, and the midfoot continues to be the most sensitive.

that discomfort ratings are influenced not only by the pain sensation while pressure is applied, but also the sensation after pressure is removed. The sensation of discomfort reported by VAS after pressure is removed is presumably affected by pressure level and foot location. Pressure at higher levels or at locations of soft tissue such as the midfoot likely creates greater tissue deformation, increasing blood reperfusion which occurs when blood returns ischemic tissue (Peirce et al., 2000). The resulting inflammation increases pain and discomfort (Cervero and Laird, 2003).

The TPO findings suggest that the pain onset when standing should occur at the location of peak pressure. However, pain onset and peak pressure were only co-located 58% of the trials. Some of

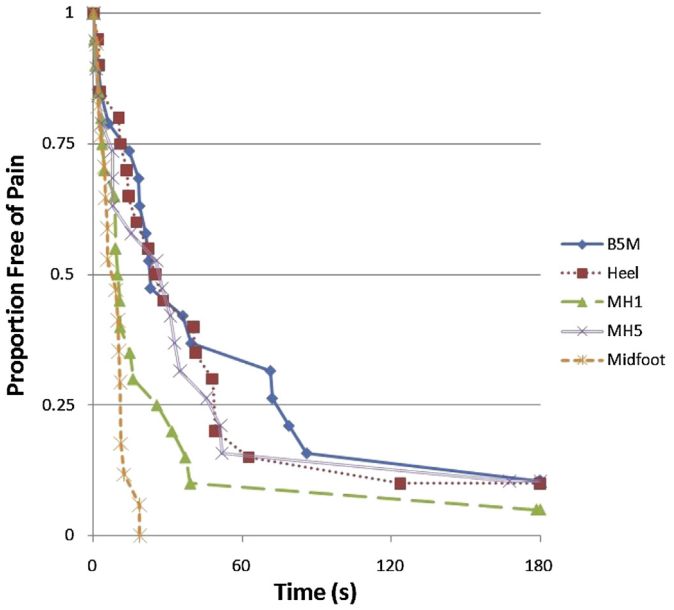


**Fig. 3.4.** Survival curves at pressure level 5 (392 kPa) for all tested foot locations. Note that all participants terminated the trial in less than 30 s at the midfoot.

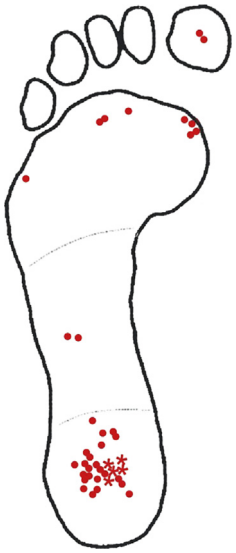

**Fig. 3.5.** Location of peak pressure for all trials. * indicates five peak pressures in the same location.

this discrepancy may be accounted for by sensitivity differences dependent on foot location. For example, Fig. 3.6 shows that pain more often originated at the first metatarsal head than the fifth, which may be a result of the greater sensitivity at the first metatarsal head. Pain origination at the first metatarsal head may further be explained by a concentration of cutaneous mechanoreceptors with large receptive fields in the metatarsal region of the plantar foot (Kennedy and Inglis, 2002). Another possible explanation for the discrepancy between the location of peak pressure and pain origin is that, during the standing pain threshold test, pressures were measured at the surface of the skin, while actual pressures in muscles and nerves deep beneath the skin could be higher or lower (Bouten et al., 2003). It is also possible that when standing, tension in muscles and ligaments (Hutton and Stokes, 1991) and shear stresses (Bennet et al., 1979) occur that also contribute to pain. These mechanisms for discomfort may account for the discrepancy between the location of peak pressure and pain.

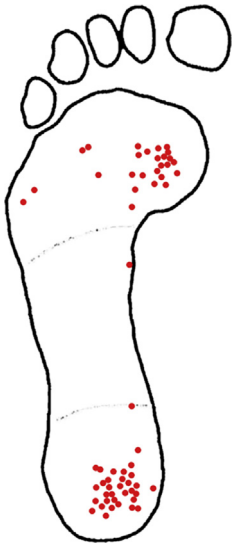

**Fig. 3.6.** Location of pain onset for all trials.

In the standing experiment, pain onset most often occurred on harder surfaces, which were associated with greater peak pressure. It appears that softer surfaces reduce discomfort by redistributing pressure over a larger contact area. As a consequence, this redistribution of pressure increases the load borne by the midfoot. Although the TPO results showed that the midfoot is most sensitive to pressure, the benefits of softer surfaces in reducing peak pressure likely outweigh the consequences of greater pressure loads on the midfoot. We hypothesize that there is a limit beyond which additional loading of the midfoot would cause increased discomfort, regardless of the benefits to reducing peak pressure. However, the pressures observed at the midfoot during standing were much smaller than the levels of pressure used in the TPO test, providing insufficient data to predict the extent to which the midfoot could be comfortably loaded. When standing barefoot on the hard surface, the midfoot was generally not loaded at all, and on the soft surface peak pressures observed in the midfoot region ranged from 17 to 41 kPa. Although the TPO pressure levels were representative of peak pressures observed at the heel and metatarsal heads during standing, they do not provide information about pain threshold for the pressures observed at the midfoot.

### 4.1. Future research

Determining the extent to which the midfoot can be comfortably loaded to decrease peak pressures at the heel and metatarsal heads is a logical extension of this research. These findings would ultimately have implications for the design of shoe inserts and footwear, in which contours and material hardness can affect peak pressures and loading of the midfoot. Another important step in predicting discomfort during standing would be an investigation of additional physiological mechanisms for discomfort in the foot (e.g., shear stresses, tension in muscles and ligaments, and focal ischemia). Future research that includes tactile sensitivity measurements such as the Semmes-Weinstein monofilament (e.g., Armstrong et al., 1998; Wiggermann et al., 2012) may explain the why the location of peak pressure is not always the same location as the onset of pain when standing. Finally, exploring the cause of variation in discomfort ratings measured after the TPO test may also help to understand how discomfort is experienced during standing. For example, measuring discomfort immediately before and after pressure is removed may help to explain the role of blood reperfusion in discomfort.

### 4.2. Limitations

This study was limited to young adults from a student population and the results may differ in older individuals. This study only evaluated the effects of pressure on pain threshold during short durations of static standing, and results may differ for typical unconstrained standing or walking.

### 4.3. Conclusions

Higher levels of pressure resulted in shorter time until pain onset, and the midfoot was the most sensitive to pressure. These results suggest that reducing peak plantar pressures and limiting the pressure on the midfoot can reduce discomfort during prolonged standing. Softer surfaces were more comfortable, and redistributed peak pressures from highly concentrated areas at the heel and metatarsal heads to the midfoot. These findings suggest that for the range of pressures observed in this study, the benefits of reducing peak pressures outweighed the consequences of increased pressure at the midfoot. Although peak pressure seems to be a good predictor of discomfort in the foot, there appear to be other mechanisms affecting discomfort that are unknown.

This research provides new information on how discomfort develops over time when the foot is exposed to static pressure. The results suggest that reducing peak pressure reduces discomfort, but that even loading across the entire foot is not ideal because of the sensitivity of the midfoot. This research also provides a measurement method that could be useful for developing and evaluating future footwear and insole designs. The methods may also be adaptable to other applications in which sustained pressure is applied to the body such as for seating or apparel like backpacks.

## Acknowledgments

Funding for this publication was made possible in part by the training grant T42 OH008455 from the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. The views expressed do not necessarily reflect the official policies of the Department of Health and Human Services, nor does mention of trade names, commercial practices, or organizations imply endorsement by the U.S. Government. The authors would also like to thank Eyvind Claxton and Charles Woolley for their help in designing and building the testing equipment.

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