The Effect of Flooring Surface Compliance on Plantar Pressures and Discomfort During Prolonged Standing

by

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ABSTRACT

Prolonged standing is common in the workplace, and is a cause of pain and discomfort in the feet, legs, and lower back. Anti-fatigue mats are often used in industry to reduce discomfort resulting from prolonged standing. However, there are currently no means for predicting the effectiveness of a particular mat in mitigating discomfort, and there is little understanding of how discomfort develops during prolonged standing. The main objective of this research was to investigate the cause of discomfort during prolonged standing, and the role of mats in reducing discomfort.

The effect of flooring material properties on discomfort and behavior was investigated during four-hour periods of standing. Touch sensitivity of the foot was also measured before and after standing to test for changes in sensitivity. Plantar pressure was investigated as a potential mechanism for discomfort during standing by testing the pain-pressure threshold at different levels of constant pressures on the foot. Finally, the effects of flooring and shoes on plantar pressure were studied.

During prolonged standing, mats reduced discomfort when compared to a hard floor, but no differences in discomfort were observed among mats. During standing, weight-shifting was correlated to discomfort and demonstrated lower statistical variance than subjective ratings of discomfort. These findings suggest that weight-shifting may offer a more sensitive measurement for discomfort than subjective ratings. Finally, as a result of prolonged standing, touch sensitivity of the feet increased, suggesting potential unintended bias in clinical touch sensitivity testing.

During pain-pressure threshold testing, elevated levels of constant plantar pressure were associated with an earlier onset of pain, indicating that plantar pressure is a mechanism that contributes discomfort. Flooring significantly affected plantar pressure during barefoot standing and walking, but when shoes were worn the effects

of flooring on pressure were very small or not significant. This suggests that for reducing plantar pressure, attention should be focused on the design of footwear rather than the design of mats. Because flooring does not affect plantar pressure, mats must reduce discomfort through some other unknown mechanism.

CHAPTER I

Introduction

Problem Statement

Prolonged standing on the job, a regular requirement for millions of workers, is associated with pain and discomfort in the lower limbs (Ryan, 1989; Madeleine, 1998) and back (Macfarlane, 1997). Flooring and footwear have been shown to have an effect on the discomfort resulting from standing (e.g., Rys, 1989; Redfern, 1995), and this has resulted in the emergence of a variety of commercially available mats and shoe inserts. However, it is not currently possible to predict which flooring and footwear designs will reduce discomfort.

A major obstacle to predicting the success of flooring and footwear is that the mechanisms for how these items affect discomfort are not well known. Ignorance of the mechanisms for discomfort creates two problems. First, without an understanding of how flooring and footwear affect discomfort, the design and selection of these products has become a process of mostly guesswork. Second, this lack of knowledge also makes it difficult to evaluate these products based on any means other than subjective ratings of discomfort, which due to lack of precision are insensitive to small differences in discomfort when comparing surfaces and footwear. The overall goal of this work is to better understand the mechanisms by which flooring and footwear affect discomfort.

Rationale

Significance

A large portion of contemporary jobs require workers to stand for prolonged periods. In Canada, a survey of over 9,000 participants sampled from the general population found that 58% worked predominantly in the standing posture (Tissot, 2005). In the United States, the classifications of cashier and retail salesperson alone constitute over 8 million workers that are often required to stand for long periods (Bureau of Labor Statistics, 2010). Prolonged standing is common in many other occupations, including health care workers (Cook, 1993; Meijsen, 2007; Baty, 1987), school teachers (Messing, 1997), and inspection and assembly workers (Redfern, 1995; Van Deen, 1998).

Despite the seemingly innocuous nature of standing as a working posture, significant health effects have been identified. Prolonged standing has been found to be a significant factor for increased risk of back pain (Macfarlane, 1997), leg and foot pain (Ryan, 1989; Madeleine, 1998) venous disorders (Tomei, 1999), and pre-term births (Mozurkewich 2000).

Interventions for Reducing Discomfort

"Anti-fatigue" mats are commonly used in industry to reduce discomfort associated with prolonged standing, and many studies have demonstrated that when compared to hard flooring, mats are capable of reducing discomfort (Rys, 1989; Redfern, 1995; Madeleine, 1998; King, 2002; Cham, 2001). The design of these studies has typically compared a hard surface (e.g., concrete) to one mat, though a few studies have evaluated multiple mats (Zhang, 1991; Redfern, 1995; Cham, 2001). Subjects were asked to stand on each surface for sessions ranging from one to four hours in a laboratory (e.g., Rys, 1989; Jorgensen, 1993; Cham, 2001), or for one week at a worksite (Redfern, 1995; King, 2002). Nearly all of the studies recorded subjective ratings of discomfort before, after, and sometimes during standing. In the majority of studies (Rys, 1989; Redfern, 1995; Madeleine, 1998; Cham, 2001; King, 2002) mats were associated with lower ratings of discomfort than hard flooring. When evaluating multiple mats, Redfern (1995) and Cham (2001) detected some differences among mats themselves, with some very soft mats appearing to be less comfortable than harder mats.

Like mats, shoe inserts (Redfern, 1995; King, 2002) and shoes with softer soles (Zhang, 1991) have been shown to effectively mitigate discomfort. These evaluations were performed using two-hour standing sessions in a laboratory (Zhang, 1991) and one-week evaluation periods in the workplace (Redfern, 1995; King, 2002). As with mats, there is little knowledge of exactly what footwear and shoe insert designs are most effective, and no ability to predict which designs will reduce discomfort.

Mechanisms for Discomfort During Standing

Most studies evaluating the effect of flooring surface on discomfort have also measured at least one physiological variable considered to be associated with a suspected mechanism for causing discomfort during prolonged standing. Fatigue of leg muscles and pooling of blood in the legs are two suspected mechanisms for discomfort during standing. However, their respective associated physiological measurements, electromyogram measures of leg muscle fatigue (e.g., Zhang, 1991; Cook, 1992) and leg volume measurements (e.g., Madeleine, 1998; Hansen, 1998; Cham, 2001) did not demonstrate differences among flooring surfaces.

A possible mechanism for how flooring and footwear affect discomfort is localized pressure on the plantar (bottom) surface of the foot. No study has yet considered plantar pressure as a mechanism for standing discomfort, though there is much evidence that suggests it may be important. Plantar pressure affects the compression of muscles, nerves, and bones in the foot when it is loaded, and high plantar pressures have been linked to foot pain and discomfort (Godfrey, 1967; Silvino, 1980). In static, barefoot standing, plantar pressure on the foot averages about 70 kPa, with peaks of around 140 kPa (Cavanagh, 1987). These values far exceed pressures of 4-

5 kPa shown to cause skin (Kosiak, 1958; Dinsdale, 1974), muscle (Sejersted, 1984), and nerve damage (Rydevik, 1981).

The most common means for determining the relationship between pressure and discomfort is the pain pressure threshold (PPT), or the level at which pain is first reported when a steadily increasing pressure is applied to a body location (e.g., Fransson-Hall, 1993; Hodge, 1999; Vaughan, 2007). Two studies have performed this test on the foot (Messing, 2001; Hodge, 2009), and the reported pressure thresholds ranged from 320 to 750 kPa depending on foot location. However, these studies do not address the relationship between pressure and discomfort for conditions similar to those of prolonged standing. The pressures measured using the traditional PPT test were much higher than those experienced during standing, and because these measurements were made with an increasing pressure, there is no information regarding how discomfort develops over time.

The Effect of Flooring on Plantar Pressure

As the relationship between plantar pressure and discomfort becomes better understood, it is increasingly important to understand how the design of flooring affects plantar pressure. Since practically all work in the occupational setting is performed while wearing shoes, it is particularly important to know whether flooring has an effect on plantar pressure when shoes are worn. Few studies have investigated the effects of flooring on plantar pressure. Mohamed (2005) found higher peak pressures when walking barefoot on concrete than on grass and carpet, but showed that these differences were not significant when shoes were worn. Similarly, Finlay (2007) measured ground reaction forces as participants walked with shoes, and did not find an effect of flooring. No studies have investigated the effect of flooring on pressures during standing, nor have any investigated interventions such as anti-fatigue mats. As a result, the effect of flooring on plantar pressure remains unknown for common workplace conditions such as when workers stand or when mats are used.

Behavioral Responses to Standing

At present, without a physiological explanation for differences in discomfort between flooring surfaces, subjective ratings of discomfort represent the only measurement available to compare mats. These subjective ratings have a low precision, making them sensitive only to very large differences in discomfort between surfaces. For example, when comparing "tiredness" ratings associated with standing on different surfaces, the coefficients of variation in Redfern (1995) were as high as 0.57. While most studies identified discomfort differences between mats and a hard control, few differences were identified among mats themselves (Redfern, 1995; Cham, 2001). There is a need for a metric with the ability to detect smaller differences in discomfort between flooring designs, preferably without extremely lengthy periods of standing.

Behavioral responses to standing such as weight-shifting between feet may provide a measurement that is sensitive to differences in discomfort between surfaces, but behavior during standing has not been properly explored. Zhang (1991) measured posture changes during standing, and identified an increase in frequency of changes with time, but not between surfaces. However, these posture changes were determined through video analysis, and the ability of this method to detect subtle changes in posture is unknown. Gregory (2008) identified behavioral responses including center of pressure (COP) shifts which were predictive of lower back pain during standing, but did not test for the effects of different flooring. Investigating postural behavior during prolonged standing may result in a useful tool for evaluating the ability of surfaces to reduce discomfort.

By studying plantar pressure as a mechanism for discomfort during prolonged standing, investigating the effect of flooring and footwear on plantar pressure, and determining touch sensitivity changes and behavioral responses to standing, this dissertation will help in understanding the causes of discomfort during prolonged standing. This line of research will lead to a significant improvement in the quality of life for the millions who stand daily on the job.

Research Objectives

The following research objectives were established:

1. Investigate the relationship between pressure and discomfort for different locations on the foot.
2. Determine the effect of flooring on plantar pressure during standing with and without footwear.
3. Examine standing behavior as a response to prolonged standing, and investigate standing behavior as a potential indicator of discomfort.

The following was established as an ancillary research objective:

a. Determine the effect of prolonged standing on touch sensitivity of the foot.

Dissertation Organization

Chapter two of this dissertation outlines an experiment which tested the effect of different flooring surfaces on discomfort during prolonged standing. In this experiment, flooring conditions were selected *a priori* based on their material properties, and behavioral responses to standing were measured to explore possible objective alternatives to subjective discomfort ratings.

Chapter three focuses on a previously unexplored relationship between prolonged standing and touch sensitivity of the foot. In the prolonged standing experiment described in Chapter two, touch sensitivity of the foot was measured before and after prolonged standing. The effect of prolonged standing on touch sensitivity is discussed for its relevance in medicine, in which touch sensitivity of the skin is commonly used for the diagnosis of peripheral neuropathy.

Chapter four introduces a pain pressure threshold test at constant pressure, which was used to determine the relationship between low levels of sustained, static pressure and the elapsed time until the onset of pain. An additional test was also performed in which the effect of flooring surface compliance on pain was measured during standing.

Chapter five of this dissertation evaluates the effect of anti-fatigue mats on plantar pressures during both standing and walking, and in shod and barefoot conditions. The effect of shoes on plantar pressures is also determined.

Chapter six provides a summary of the findings of this research, discusses the implications for the design of flooring and footwear, and suggests topics for future work.

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CHAPTER II

Effects of Flooring on Discomfort and Behavioral Responses During Prolonged Standing

Abstract

Objective: This experiment investigated the effects of flooring surfaces on perceived discomfort during prolonged standing, and also measured behavioral responses such as frequency of weight-shifting between the feet.

Background: Prolonged standing is a common requirement in the workplace and is a well-known cause of discomfort. Anti-fatigue mats have been shown to reduce discomfort resulting from standing, but no study has identified a particular mat which performs better than others.

Methods: Participants stood for four hours on each of four commercially-available “anti-fatigue” mats and a hard surface (control condition). Subjective ratings of discomfort were measured, and in-shoe pressure was recorded and used to determine weight-shifting during standing.

Results: Compared to the control condition, discomfort after four hours of standing was reduced in three of the four mats, but discomfort ratings did not significantly differ among mats. The frequency of weight-shifting was affected by flooring surface and was positively correlated to discomfort.

Conclusion: These results suggest that differences in discomfort among mats are undetectable using subjective ratings of discomfort. Behavioral responses to standing, specifically weight-shifting between feet, may provide an objective alternative to subjective reports of perceived discomfort.

Introduction

Significance

Standing for prolonged periods of time is required for employees in many occupations, including health care workers (Baty, 1987; Cook, 1993; Meijsen, 2007), supermarket workers (Ryan, 1989), school teachers (Messing, 1997), and inspection and assembly workers (Redfern, 1995; Van Deen, 1998). While prolonged standing is common, its consequences are not trivial. Over the course of hours, prolonged standing has been shown to cause discomfort in the feet, legs, and lower back (Madeleine, 1998; Jorgensen, 1998; Cham, 2001). Regular exposure to prolonged standing has been associated with an increased risk of back pain (Macfarlane, 1997), leg and foot pain (Ryan, 1989) venous disorders (Tomei, 1999), and pre-term births (Mozurkewich 2000).

Anti-Fatigue Mats and Discomfort

Anti-fatigue mats are commonly used in industry to reduce discomfort resulting from prolonged standing. Several studies have evaluated mats by comparing at least one mat to a hard control surface. In these experiments, participants were asked to stand on each surface for sessions ranging from one to four hours in a laboratory (e.g., Rys, 1989; Madeleine, 1998; Cham, 2001), or for one week at a worksite (Redfern, 1995; King, 2002). Nearly all of the studies recorded subjective ratings of overall discomfort after standing (e.g., Hansen, 1997; Madeleine, 1998), and many also recorded discomfort ratings by body region (Zhang, 1991; Redfern, 1995; Cham, 2001; King, 2002). In the majority of studies (Rys, 1989; Redfern, 1995; Madeleine, 1998; Cham, 2001; King, 2002) mats were found to be associated with lower ratings of discomfort when compared to hard flooring. Redfern (1995) and Cham (2001) evaluated multiple mats and detected differences among mats themselves. These studies found that very soft mats (mats with a very low stiffness, defined below) were sometimes associated with higher discomfort than relatively harder mats. However, neither study was able to identify a particular mat that was more comfortable than other mats. The general conclusion that can be drawn from previous studies is therefore somewhat limited; that very hard surfaces are undesirable for standing, and that very soft surfaces may also be undesirable. There is currently no means for predicting the effectiveness of a particular mat in mitigating discomfort.

Behavioral Responses to Standing

Part of the reason it is difficult to predict the ability of mats to reduce discomfort during prolonged standing is because there currently is no physiological explanation for differences in discomfort among flooring surfaces (Redfern, 2001). Without physiological measurements that can differentiate effects of different flooring surfaces, subjective ratings of discomfort represent the only measurement available. These subjective ratings have a large variability, making them sensitive only to very large differences in discomfort between surfaces. For example, when comparing subjective ratings associated with standing on different surfaces, the coefficients of variation in Redfern (1995) were as high as 0.57. There is a need for a metric with the ability to detect smaller differences in discomfort when comparing flooring designs.

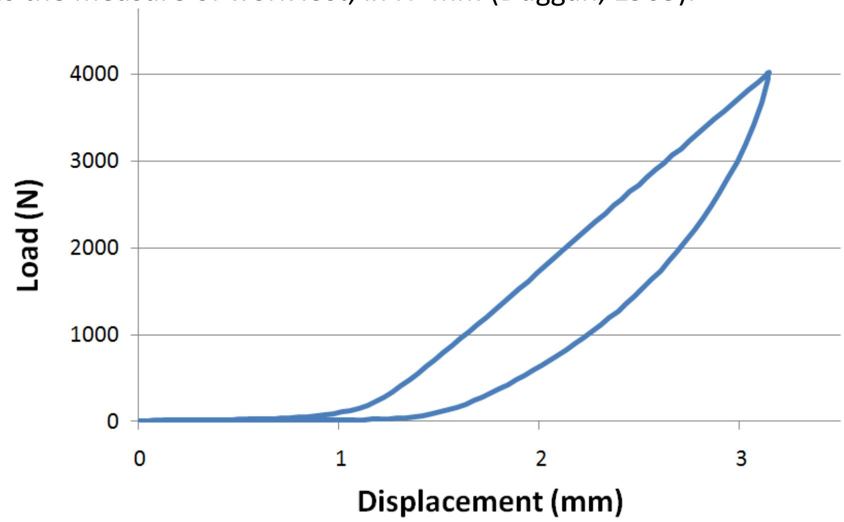
Behavioral responses to standing such as weight-shifting between the feet may provide a measurement that is sensitive to differences in discomfort between surfaces. The behavioral response to standing hasn't been thoroughly explored, but there is some initial evidence to suggest it may be related to discomfort. Gregory (2008) found that center of pressure (COP) shifts were predictive of lower back pain during standing, but did not test for the effects of different flooring. Cham (2001) found some significant differences in lateral COP shifts after three hours of standing, showing greater shifts for some surfaces associated with higher discomfort ratings. Through subjective video analysis Zhang (1991) counted posture changes during standing. The study identified an increase in the frequency of changes with time, but not among surfaces.

Flooring Material Properties

Another impediment to predicting the ability of mats to mitigate discomfort is that the material properties of mats have not been adequately described in most previous studies. Studies that fail to measure and report material properties of flooring are difficult to reproduce, and the results cannot be used to predict the performance of other unstudied mats. When comparing anti-fatigue mats, some studies provide as little description as thickness and material composition (e.g., Zhang, 1991; King, 2002), neglecting additives, coatings, and geometric structure of mats that can drastically alter their attributes (Ciullo, 1999). The greatest detail was given by Cham (2001) where mats were described using several flooring properties. However, no study has measured properties *a priori* to allow strategic selection of mats that include a range of values representative of the population of commercially available mats.

The most appropriate material properties to describe mats are likely stiffness and "work lost," which appear to be connected to discomfort during standing. Stiffness is a material's resistance to deformation (compression) when an external load is applied. Work lost represents the energy absorbency of a material. When a material is compressed, and the compression force is graphed against displacement, stiffness is represented by the slope of the linear portion of the curve (Beer, 2002). Work lost represents the area between compression, and a curve measured during subsequent decompression (Duggan, 1965). (See Figure 1.1). Goonetilleke (1999) considered several material properties for shoes, and found that stiffness was most highly correlated to "perceived levels of cushioning" during standing. Cham (2001) found trends in discomfort associated with flooring surfaces, stating that greater stiffness and lower work lost were associated with lower discomfort ratings.

Figure 2.1. Graph of force vs. displacement as an anti-fatigue mat is compressed and unloaded. The linear portion of the graph is generated as the compression load on the mat is increased. The slope of this line is the measure of the stiffness, in N/mm (Beer, 2002). The curved portion of the graph is generated as the compression load is subsequently decreased. The area between the compression and decompression curves is the measure of work lost, in N*mm (Duggan, 1965).



Research Objectives

This study had two primary objectives. The first was to investigate the effect of flooring on discomfort by evaluating anti-fatigue mats with material properties that are representative of a range of contemporary commercially-available mats. The second objective was to measure several behavioral responses to prolonged standing, and to determine how these responses were affected by flooring surface, and how they correlated to discomfort.

Methods

In this study, participants stood for four hours on different flooring surfaces. During this time, pressure on the plantar surface of the foot was measured using in-shoe pressure sensors. These pressure data were used to assess the behavioral response to standing. Subjective ratings of discomfort were also measured.

Participants

Ten participants (five male, five female) were recruited from a student population. The mean age of participants was 23.5 years (SD 4.1 years) and their mean body mass was 67.4 kg (SD 12.6 kg). The women's shoe sizes (U.S. sizing) ranged 6-10 and the men's ranged 7.5-12. Individuals with a history of lower extremity disorders and those with an irregular foot arch height were excluded.

Selection of Anti-Fatigue Mats

The independent variable in this experiment was the flooring surface. The material properties of stiffness and work lost were measured for seventeen commercially available mats, from which four mats were chosen for the experiment. Material properties of the mats were measured using an MTS testing machine (model: Insight 10 SL; MTS Systems Corp; Eden Prairie, MN, USA) in which a sample of each mat was placed between two round aluminum plates 15.3 cm diameter. Stiffness and work lost were calculated by taking the average of three compression cycles to 4000 N.

Figure 2.2 shows a graph of the values of stiffness versus work lost for all 17 mats considered for the study. The selected mats (A through D) were chosen to represent the range of properties observed in the larger sample of 17 mats. Experimental design considerations were also a factor in selection, such as the inclusion of mats B and C with similar work lost values in an attempt to isolate the effect of stiffness on experimental outcomes. The control surface was linoleum tile on concrete. While this surface could not be measured in the MTS machine, it was characterized by a very large stiffness and a very small work lost. Table 2.1 shows the material properties for the four mats included in the study.

Figure 2.2: Stiffness and Work Lost values of commercially available mats considered for the study. Mats selected for the study are labeled.

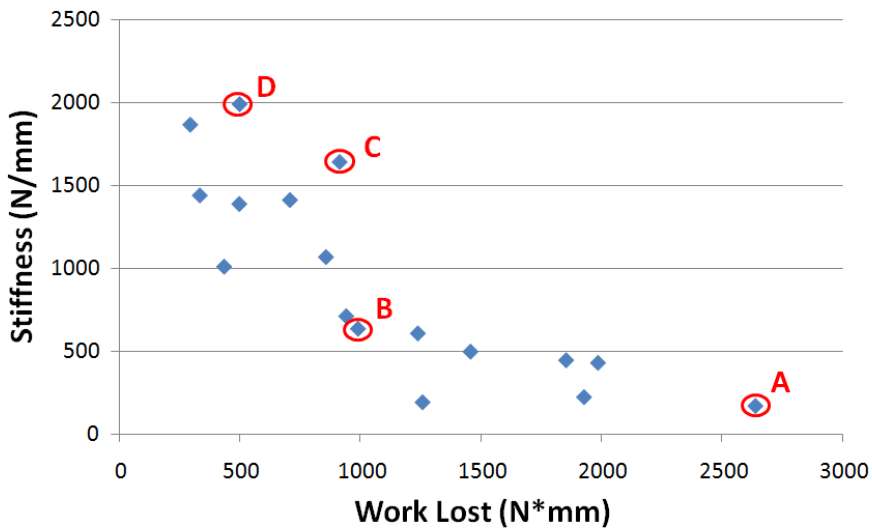


Table 2.1: Stiffness and Work Lost values of mats chosen for the study.

	Stiffness (N/mm)		Work Lost (N*mm)	
Surface	Mean	Std. Dev.	Mean	Std. Dev.
A (“softest”)	169	2.0	2638	73.0
B (“softer”)	711	65.9	942	68.0
C (“harder”)	1639	217.1	914	10.4
D (“hardest”)	1988	57.7	500	82.0

Procedure

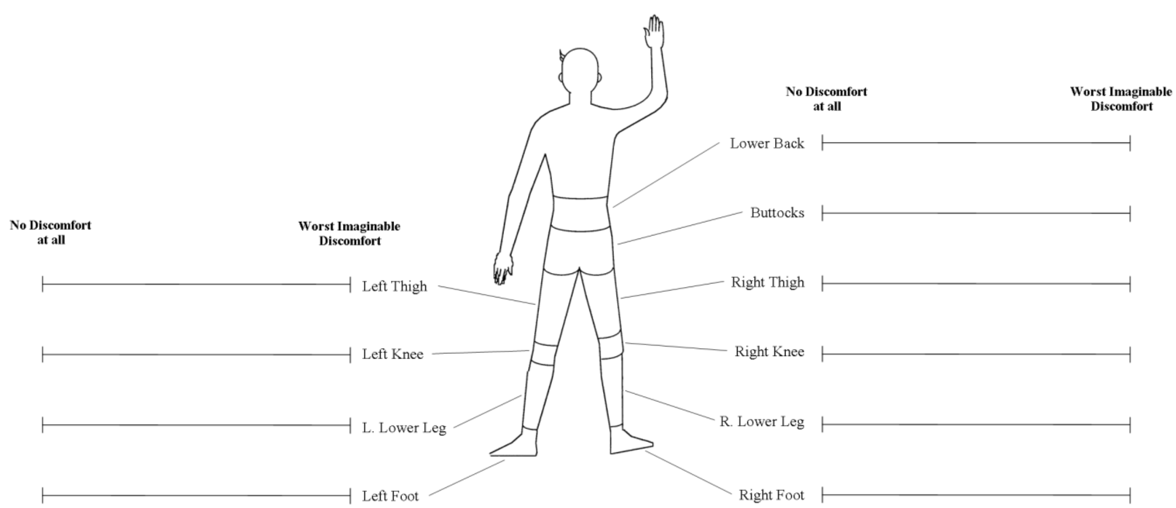
Each participant attended five experimental sessions, each lasting four hours. Using a full-factorial design, participants stood on a different surface for each session, and these surfaces were presented in a random order. To control for physiological time-of-day effects (e.g., Lericollais, 2009), data collection for each participant occurred at the same time of day. For each participant, sessions were scheduled at least 72 hours apart to allow ample recovery from fatigue. Experimental sessions for all participants were completed within the same eight-week period.

Participants were provided with standardized socks and cross-trainer athletic shoes to wear (New Balance™ model MX602WN for men, and the similar model WL493WF for women). Participants stood at an adjustable height work table in a 1.0 by 1.5 meter rectangular area, and were instructed not to use the table to support any weight except that of the forearms. No instructions or constraints to standing were otherwise given. To standardize the demands on each participant, a rotation of work tasks was performed which consisted of a light assembly task, a typing task, and a continuous monitoring task on a computer. After 110 minutes of standing, participants were given a ten minute break during which time they were permitted to walk or sit as they wished.

Discomfort Ratings

Before the experiment and after each 55 minutes of standing, a discomfort survey was administered (see Figure 2.3). This survey used ten-centimeter visual analog scales (Capodaglio, 2001) for determining overall ("overall leg" and "overall body") and localized discomfort ratings (feet, lower legs, knees, thighs, buttocks, and lower back) presented on a body diagram similar to Corlett (1976). (See figure 2.3).

Figure 2.3: Survey used to measure discomfort at various body locations (not shown to actual scale)



Measurement of Behavioral Responses

Prior to data collection, 0.13 mm thick F-Scan® pressure sensing insoles (Tekscan; Boston, MA, USA) were cut to fit and placed in the participant's shoes. These insoles are composed of a grid of 0.51 cm x 0.51 cm "sensels" that measure pressure by electrical resistance. Ten minutes of in-shoe pressure data were collected at 20 Hz during the computer monitoring task, which occurred near the end of each hour of standing. The pressure data were used to determine several behavioral responses to standing, including weight-shifting, COP excursions, and distribution of body weight between the left and right foot.

Weight-Shifting was defined as a change in distribution of load bearing between the two feet, and consisted of a transition between any of the three conditions: 1) greater than 80% of body weight on left foot, 2) greater than 80% of body weight on right foot, 3) at least 20% of body weight on each foot. These shifts were counted during each ten-minute pressure recording. Changes that occurred less than 7.5 seconds after a previously-counted weight-shift were considered part of a continuous shifting motion, and were not counted as a separate shift.

COP Excursions were the average travel rate (cm/sec) of the COP on a single foot during a standing experimental condition. Excursions were analyzed separately in the medial-lateral (ML) direction and the anterior-posterior (AP) direction and were calculated using only observations when the foot was loaded with at least 20% of body weight. COP excursions were measured within-foot rather than for the whole body to provide an estimate of more subtle movements of the foot and ankle, in contrast to weight-shifting which measured whole-body postural movement.

The distribution of body weight between the left and right foot during standing was characterized as one of two stances: a predominantly single-foot stance (1FS) characterized by at least 80% of the body weight supported by one foot, or a two-foot stance (2FS) with at least 20% of body weight supported by each foot.

Statistical Analysis

Subjective discomfort ratings and behavioral responses (weight-shifting, COP excursions, and percentage of time in 1FS) were analyzed independently using a repeated measures analysis of variance (Montgomery, 2005). The effect of session number, duration of standing (by hour), surface, and participant (as a fixed effect) were included in the models. Discomfort ratings were analyzed as potential covariates for behavioral responses. Where surface was significant, Tukey pair-wise comparisons were performed. Linear regression models were also generated to test for the ability of the mat material properties of stiffness and work lost to predict discomfort and behavioral responses.

Discomfort data were normalized by subtracting initial discomfort ratings from subsequent ratings obtained during the same session. Outliers in discomfort ratings were not uncommon, and any values with an associated studentized residual greater than three standard deviations were removed from the analysis. All significant findings related to discomfort ratings were dependent upon the removal of outliers.

Results

Discomfort Ratings

Of the eight body locations on the discomfort survey, only the lower leg was significantly influenced by surface across all hours of the experiment. Significant flooring effects only appeared in other locations when fourth-hour ratings were compared. For the "overall leg," the softest mats, A and B, demonstrated significantly ($p < 0.05$) lower discomfort ratings than the hard linoleum-on-concrete control (see figure 2.4). For the lower leg, surfaces A and D, the hardest and softest mats, showed significantly lower discomfort ratings than the hard control (see figure 2.5). For the feet, only the softest mat (surface A) showed a significant reduction in discomfort ratings over the hard control (see figure 2.6) After four hours of standing, the hard control surface tended to exhibit greater discomfort than mats for the lower back ($p = 0.07$) and the knees (p = 0.07). Flooring had no significant effect on discomfort for the overall body, buttocks, or thighs. The properties of stiffness and work lost were not related to any ratings of discomfort except for the foot, where increasing stiffness and decreasing work lost corresponded to increased discomfort.

Figure 2.4: Mean overall leg discomfort for the different flooring surfaces. Error bars represent standard error of the mean. *Significant difference in pairwise comparison.

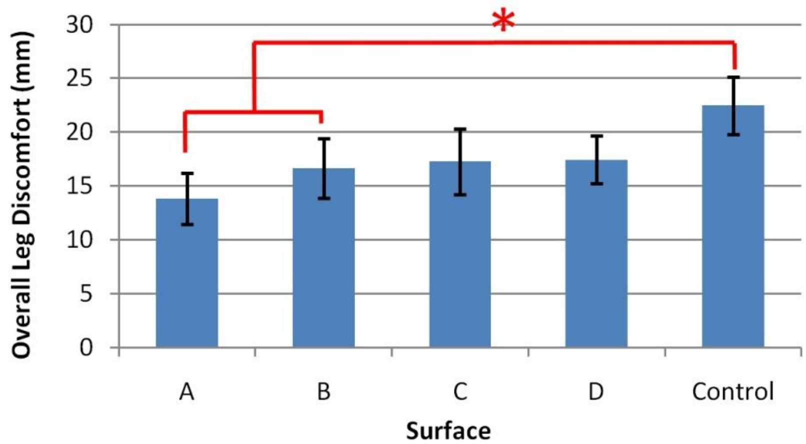


Figure 2.5: Lower leg discomfort for the different flooring surfaces. Error bars represent standard error of the mean. *Significant difference in pairwise comparison.

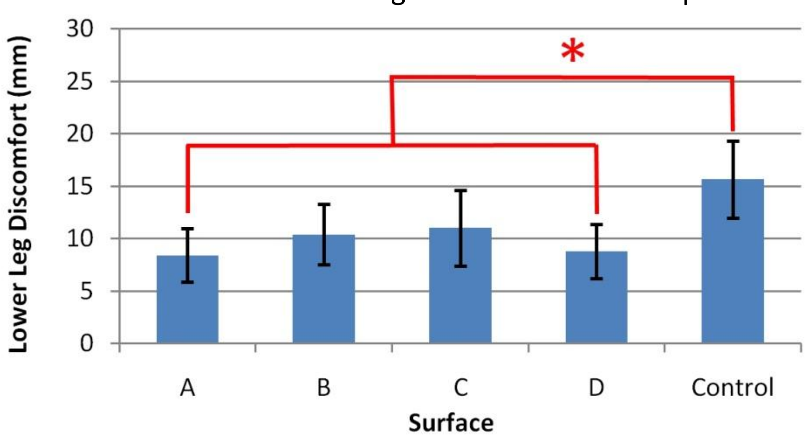
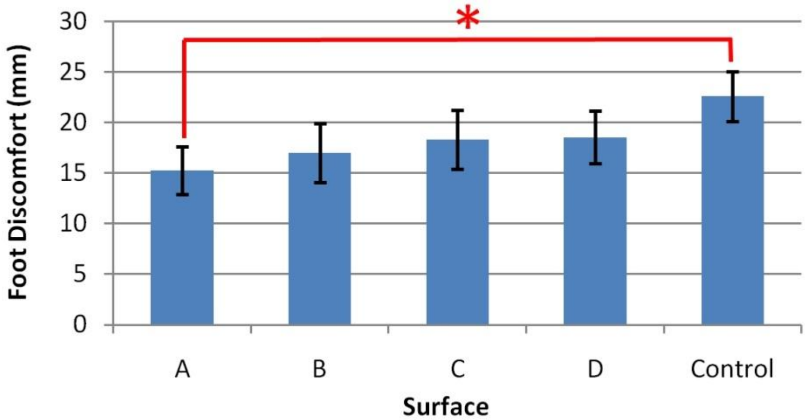


Figure 2.6: Foot discomfort for the different flooring surfaces. Error bars represent standard error of the mean. *Significant difference in pairwise comparison.



Behavior – Weight-shifting

The number of weight-shifts was significantly affected by the session number ($p = 0.01$); standing duration ($p = 0.01$); and surface ($p < 0.01$). Weight-shifting increased with session and elapsed hours standing, and the hardest mat (surface D) corresponded to significantly more shifts than the soft mats (A, and B) and the hard control. (See Figure 2.7). Weight-shifting was positively correlated with foot discomfort ($p < 0.01$), lower back discomfort ($p = 0.01$), overall leg discomfort ($p = 0.01$), and tended to increase with overall discomfort ($p = 0.06$). Figure 2.8 shows the trend of increasing weight-shifting associated with increasing foot discomfort. The material properties of stiffness and work lost were not related to weight-shifting.

Figure 2.7: The mean frequency of weight-shifts (counted in a ten minute period) for each surface. Error bars represent standard error of the mean. *Significant difference in pairwise comparison.

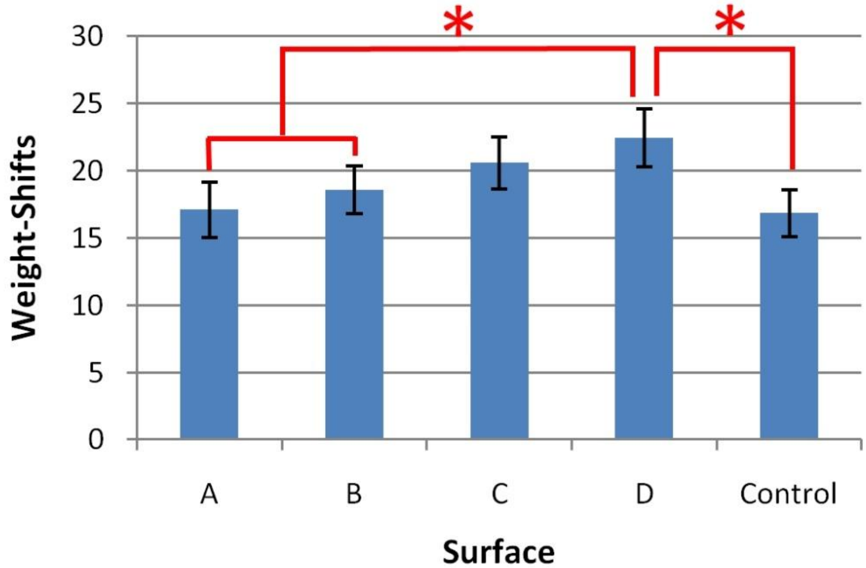
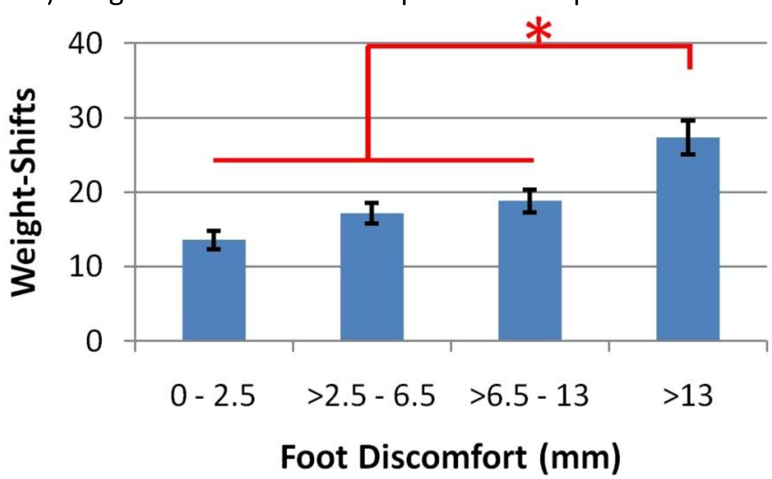
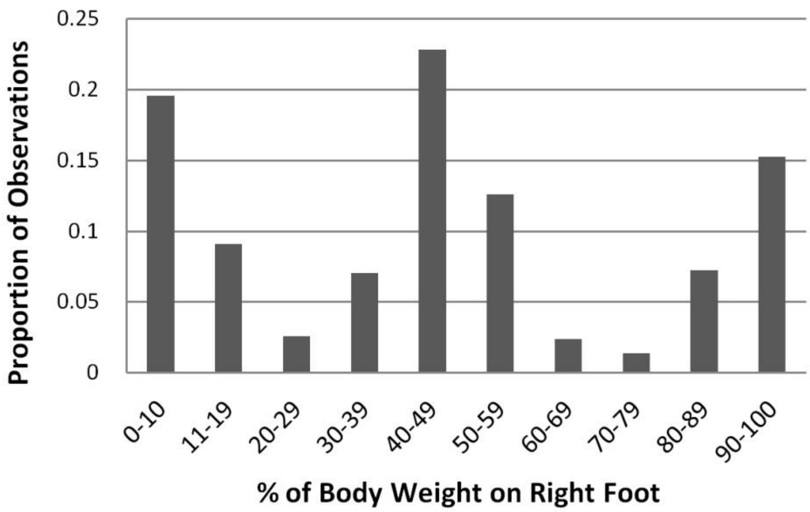


Figure 2.8: All normalized discomfort ratings are placed into quartiles (n=54 for each bin). The means of the number of weight-shifts per ten-minute period are shown for each quartile of foot discomfort ratings (error bars represent standard error of the mean). *Significant difference in pairwise comparison.



An analysis of the weight-bearing between the left and right foot across all participants and all trials showed a trimodal distribution, in which standing tended to occur with either greater than 80% of body weight on a single foot (51% of observations), or relatively balanced with 40-60% of body weight on each foot (35% of observations). Figure 2.9 shows the proportion of observations for different relative loading between feet.

Figure 2.9: Distribution of body weight between feet during standing

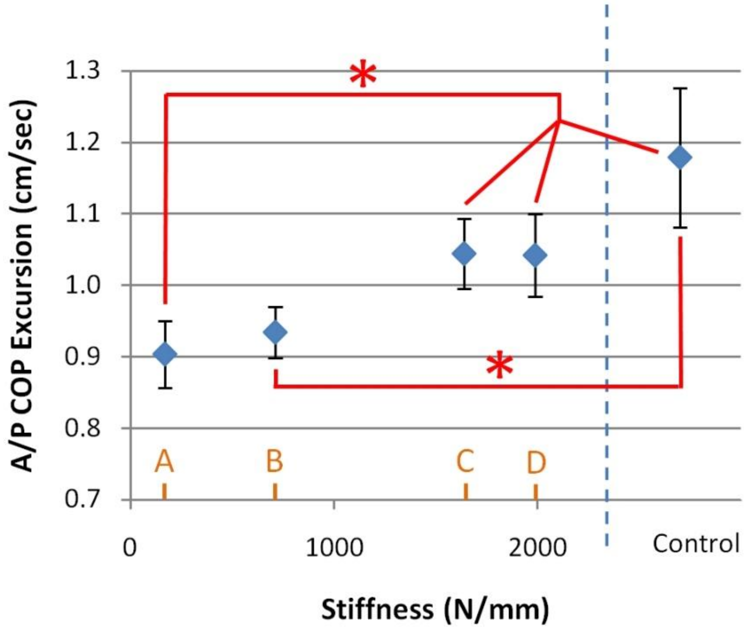


The percentage of single foot stance (1FS) increased with standing duration ($p = 0.03$), and was positively correlated with discomfort ratings ($p = 0.01$). Material properties of stiffness and work lost were not related to the percentage of 1FS.

Behavior – COP Excursions

ML and AP COP excursions also increased with discomfort ($p = 0.01$ and $p < 0.01$ respectively). The effect of surface was significant for both ML and AP Excursions ($p < 0.01$ for both). For ML Excursion, the soft mats (surfaces A and B) showed significantly less travel than the harder mat (surface C) and the hard control. For AP excursions, the softest mat (surface A) demonstrated significantly less travel than the harder mats (surfaces C and D) and the control; and the softer mat (surface B) had significantly less travel than the hard control. Figure 2.10 shows mean AP excursions by surface. Mean ML excursions by surface (not shown) followed very similar trends. Stiffness and work lost were both predictive of AP excursions ($p < 0.01$ and $p = 0.04$, respectively).

Figure 2.10: Mean anterior-posterior excursions for each flooring surface graphed against the stiffness of the surface. Each surface is labeled above the x-axis. Error bars represent standard error of the mean. *Significant difference in pairwise comparison.



Discussion and Conclusions

Discomfort Ratings

The hard control surface was associated with significantly higher discomfort ratings than three of the mats. This reinforces the findings of other studies that also found differences in discomfort (Rys, 1989; Redfern, 1995; Madeleine, 1998; Cham, 2001; King, 2002). With the exception of the lower leg, which was significant throughout all four hours of the experiment, significant differences in discomfort ratings did not emerge until the fourth hour. This is consistent with the findings of Cham (2001), who found significant differences only during the third and fourth hours.

This study did not find differences in discomfort among the mats themselves, which is in contrast to findings reported by Redfern (1995) and Cham (2001). A possible explanation for the lack of differences among mats is that those included in this study were all contemporary commercially-successful mats. It is possible that ineffective mats which could result in higher discomfort ratings, therefore making differences in discomfort easier to detect, have disappeared from the market. For example, some of the less comfortable mats in Redfern (1995) and Cham's (2001) studies were very soft and "bottomed out" when loaded. A surface that bottoms out is easily deformed when loaded and becomes much harder after it is compressed. The mats used in this study were similar in stiffness to those used in Redfern (1995) and Cham's (2001) studies, but did not bottom out when loaded.

Behavior

All of the behavioral responses measured in this study (weight-shifting, % time in 1FS, ML and AP excursions) were positively correlated with discomfort. A post-hoc statistical power analysis showed that behavioral response variables were better able to discriminate among mats than subjective ratings of discomfort. Given the differences in means observed in this study, for an alpha = 0.05 and a power of 0.90, 105 participants would be required to detect a difference among mats using discomfort ratings, 49 would be required for weight-shifting, and 25 would be required for COP excursions. Understanding the relationship between discomfort and behavior may help establish behavioral responses as a potential alternative to subjective ratings for evaluating discomfort, and may also provide clues for how fatigue and discomfort develop during standing.

Weight-shifting seems to be a particularly promising response variable for evaluating flooring because of its likely connection to physiological mechanisms for discomfort. For example, it has been suggested that shifting weight temporarily relieves pressure on the feet (Goonetilleke, 1998), allows replenishment of synovial fluid in joint cartilage (Alexander, 1992), and decreases venous pooling in the lower extremities (Brantingham, 1970). In this study, weight-shifting was positively correlated with discomfort. Weight-shifting generally seemed to increase as flooring stiffness increased, but this trend was not consistent for the hard control surface. One possible explanation is that the increased COP excursions observed for the hard control surface compensated for the need to shift weight between the feet.

COP excursion is another behavioral response variable that may be suitable for evaluating flooring. Like weight-shifting, COP excursions were correlated with discomfort, and have a potential connection to physiological mechanisms for discomfort. Because fatigue of leg muscles has been shown to cause an increase in COP excursions (e.g., Vuillerme, 2002), excursions may provide an indirect measure of leg muscle fatigue. COP excursions showed a consistent trend with respect to flooring stiffness, with increasing stiffness corresponding to larger AP excursions. It is possible that on these less comfortable, harder surfaces, individuals respond with COP excursions to alter the distribution of tension in muscles and pressure in cartilage. Additional research is needed to evaluate these relationships between COP excursion and flooring stiffness, and COP excursion and discomfort.

Discomfort and Performance

This study investigated the effect of discomfort and fatigue resulting from prolonged standing on performance of simulated work tasks and functional tests, but these results did not yield significant findings. The work tasks (i.e., typing, assembly, and computer monitoring) were performed during standing and the performance on these tasks was measured to test for effects of standing. Additionally, two functional tests were administered before and after standing. A digit symbol substitution test (Proust-Lima, 2007) was administered to test for a change in cognitive ability, and a "foot tapping" test which was an adaptation of Fitts' task (Fitts, 1954) for the foot was conducted to test for a change in motor control. Four hours of standing did not result in diminished performance in any of these tests. However, the typing and assembly tasks also demonstrated significant learning effects, so it is difficult to draw a conclusion about the effects of standing for those work tasks. These tasks were also repetitive in nature, and the effect of standing was not tested for performance in non-repetitive tasks, or tasks that require higher levels of cognitive processing. Finally, it is possible that differences in task performance not observed after four hours of standing may emerge after days or weeks of continued exposure to standing.

Limitations

This study tested participants from a student population which does not represent the demographics of the general work force. Participants stood unconstrained in a small 1.0 by 1.5 meter area, and the results may have been different for purely constrained standing or for a mixture of standing and walking. While the standardized footwear used in this experiment helped to reduce unwanted variability, it is possible that different shoes or insoles may yield different results.

There are several possibilities for why differences in discomfort that may occur in the workplace were not detected in this experiment. The large variability of the subjective ratings of discomfort makes finding significant discomfort differences between surfaces difficult in trials of four-hour duration. While the four hours of standing time in this study was longer than most previous laboratory studies, the time duration may not capture all of the outcomes that might otherwise be seen with consecutive days of exposure to 8 to 12-hour work shifts as could be experienced in industry.

Future Work

More work is needed to explain the physiological mechanisms for how mats intervene to reduce discomfort as compared to standing on a hard surface. The behavioral results from this study suggest that comfortable flooring may provide greater stability, reducing muscle requirements to maintain an upright posture. Electromyography of leg and lower back muscles during standing could be used to test the hypothesis that smaller COP excursions are associated with reduced muscle activation. To provide a biomechanical explanation for this phenomenon, a cadaveric foot could be used to test the hypothesis that a perturbation of a certain torque about the ankle for a loaded foot on a soft surface will generate a smaller COP excursion than the same level of torque for a loaded foot on a hard surface.

More comfortable flooring may also allow enable discomfort relieving movements while standing. Using motion capture or goniometers to measure movement of the ankle, knee, hip, and lumbosacral joint will test the hypothesis that softer flooring enables greater changes in joint angles while standing. This result could then be linked to venous pooling, previously associated with discomfort (Kraemer, 2000), by testing the ability of these joint movements to reduce leg circumference, a measure of venous pooling. These movements may also identify an alternate compensatory strategy that explains the inconsistent weight-shifting result that was observed on the hard control surface in this study.

Implications for Industry

This study did not detect differences in discomfort between four commercially-available mats, but out results confirm that mats are indeed capable of mitigating discomfort during prolonged standing, There are many reasons why differences between mats may exist but are not detectable (e.g., variability in discomfort ratings, difference in individual preference, etc.). However, these findings do suggest that for standing workstations, the selection of mats can be based more on criteria such as cost, durability, and safety and less on perception of comfort.

The results also show that while mats reduce discomfort, the effect of hours spent standing is much greater than the effect of flooring surface. This means that eliminating standing work, using sit/stand stations, or rotating seated and standing tasks will provide greatest comfort to the worker, regardless of flooring surface.

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CHAPTER III

The Effect of Prolonged Standing on Touch Sensitivity Threshold of the Foot

Abstract

Objective: The objective of this research was to determine the effect of prolonged standing on touch sensitivity of the foot.

Design: Observational study with replications.

Setting: University laboratory.

Participants: Ten healthy college students (five male and five female) with mean age of 23.5 years (SD 4.1 years) and mean body mass of 67.4 kg (SD 12.6 kg).

Methods: Semmes-Weinstein Monofilament (SWM) tests were administered to twelve locations on the dorsal and plantar surfaces of the foot before and after four hours of standing. These locations were formed into several groupings (toes, metatarsal heads, midfoot, heel, all plantar sites, and all dorsal sites) and paired t-tests were used to test for significant changes in sensitivity threshold after standing.

Main Outcome Measurement: The difference between sensitivity thresholds measured before and after standing for different locations on the foot.

Results: The average of all sensitivity thresholds on the plantar surface of the foot dropped from 0.56 to 0.36 grams-force ($p < 0.01$) following four hours of prolonged standing. This change in threshold equated to a difference of one SWM level. Changes in the sensitivity threshold of the dorsal aspect of the foot were not significant.

Conclusions: The results suggest that the plantar foot has greater sensitivity to touch after prolonged standing. These findings may be useful for identifying potential unintended bias in clinical touch sensitivity testing. Future research is necessary understand the underlying mechanisms for this sensitivity change, and to determine the

onset and recovery times for sensitivity changes.

Introduction

Peripheral neuropathy is a disorder of the peripheral sensory, motor, and/or autonomic nerves. There is a high prevalence of peripheral neuropathy in persons who have long-standing diabetes, with more than 50% developing the disorder (Eastman, 1995). The most common form of peripheral neuropathy is distal symmetric polyneuropathy which affects the longest nerves first and progresses proximally (Eastman, 1995). This polyneuropathy affects the A-beta nerves which detect touch sensation, and is characterized by tingling, numbness, and pain (Woolf, 1994). Prompt diagnosis is important for managing the disease and preventing complications resulting in foot ulcers (McNeely, 1995) and amputation (Pecoraro, 1990).

Assessment of touch sensation through psychosomatosensory threshold tests provides a rapid, comfortable, and inexpensive assessment of sensory function. This is clinically important in the evaluation of patients at risk for peripheral neuropathy. The most commonly used psychosomatosensory threshold test is the Semmes-Weinstein monofilament (SWM) which has demonstrated effectiveness in detecting risk for foot ulceration (Bell-Krotoski, 1987; Armstrong, 1998). The nylon Semmes-Weinstein monofilaments vary in stiffness to allow for determination of the threshold for touch sensitivity. The SWM is commonly used in two ways, either by employing a single filament to test for sensitivity at a critical level, or by testing with a range of filaments to determine an exact sensitivity threshold. Much clinical research into the use of SWM has focused on using a single monofilament, the 5.07 level corresponding to 10 grams-force, for this prediction of risk for foot ulceration.

Substantial research has been performed to determine the reliability and validity of *measures* of touch sensitivity (e.g., Valk, 1997; Armstrong, 1998; Mayfield, 2000), but to our knowledge none has investigated temporal variability of foot sensitivity itself, including the effects of exposure to activities of daily living. The objective of this research was to determine the effect of prolonged standing on touch sensitivity of the foot.

Materials and Methods

Measurement Instrument

Semmes-Weinstein monofilaments were selected as the measurement instrument, (supplied by Timely Neuropathy Testing LLC, Ventress, Louisiana) and were calibrated by the author using an electronic gram scale (Acculab V-200, Bohemia, NY). These values, determined by calibration, deviated moderately from specified values and are presented in Table 1. Measured values were recorded as the average of three measurements following a two cycle "break-in" period for each monofilament (Booth, 2000).

Table 3.1: Mean and (standard deviation) of actual measured values of Semmes-Weinstein monofilaments.

Filament	Specified (g)	Measured (g)
2.83	0.07	0.06 (0.01)
3.22	0.16	0.15 (0.01)
3.61	0.40	0.24 (0.01)
3.84	0.60	0.42 (0.01)
4.08	1.00	0.67 (0.01)
4.17	1.40	1.09 (0.03)
4.31	2.00	2.43 (0.06)

Experimental Design

This research was part of a larger experiment that utilized ten subjects (five male, five female) with mean age of 23.5 years (SD 4.1 years) and mean body mass of 67.4 kg (SD 12.6 kg). Subjects reported no history of peripheral neuropathy, numbness or tingling in the feet, or diabetes. Approval for use of human subjects for this experiment was obtained from the University's Institutional Review Board. Subjects stood in a climate-controlled room for four hours interrupted by a ten-minute seated break after the first two hours. All subjects wore the same brand and model of athletic shoe and socks. The purpose of this larger experiment was to measure the effect of anti-fatigue mats on discomfort during prolonged standing. SWM foot sensitivity measures were made immediately before and after each of 42 experimental sessions. Each subject participated in three to six sessions in which the protocol remained unchanged except for the flooring surface used (a hard linoleum tile floor and anti-fatigue mats).

Testing Procedure

SWM sensory testing was conducted in a manner similar to Hodge (2009). When the SWM test was administered, participants removed their shoes and socks, closed their eyes, and returned an affirmative response when a filament was sensed. Sensitivity was tested at eight sites on the plantar surface and four sites on the dorsal surface of the dominant foot (shown in figure 3.1). A variety of locations around the foot were chosen from sites identified in previous publications to be significant for providing protective sensation for the development of diabetic ulcers (Mayfield, 2000; Modowal, 2006). However, due to the large number of measurements performed, the number of locations was limited to reduce the overall testing time.

Figure 3.1: Locations tested on plantar (left) and dorsal (right) surface of the foot

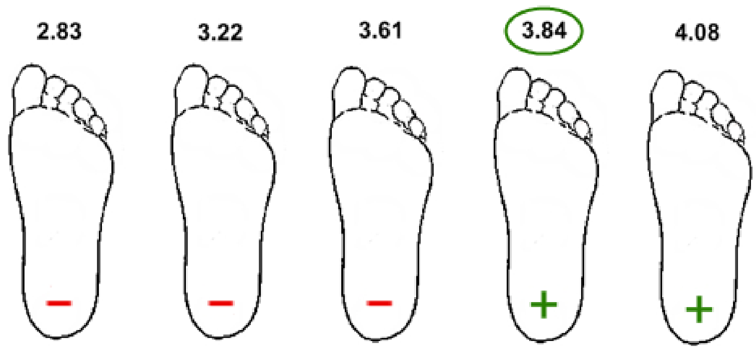
Locations were tested in random order with irregular pauses between each application. Whenever possible, calluses and hair at the testing locations were avoided. At each site, the monofilament was gently pressed perpendicularly against the skin surface until the filament bowed. Pressure was held for approximately 1.5 seconds and then removed. If the subject did not elicit a positive sensation response during the initial test with a filament at a given site, a second application was given, following the random order. A positive response was recorded if sensation was reported for at least one of the two applications with a given filament. Because of the irregular pauses between applications, no null stimulus condition was used. If after an application a response was unusually early or late, participants were asked to identify the location of the sensation to rule out false positive responses. Testing began with 2.83 as the thinnest filament level, and filaments were increased incrementally until all twelve sites were felt for a single level.

With this protocol, the sensitivity threshold for all twelve locations could be tested in about five minutes. Speed was important because the objective of the study was to measure temporal changes in touch sensitivity, and the rate of recovery to normative values after prolonged standing is unknown. Additionally, the SWM requires active concentration by the subject and after four hours of standing boredom and fatigue associated with a long test was a concern. For these reasons, more sophisticated sensitivity threshold testing methods such as stepping algorithms which can average up to five minutes per testing location (Dyck, 1993; Berquin, 2010) were not used.

Data Analysis

For the purpose of numerical analysis, Semmes-Weinstein monofilament levels were converted to units of gram-force. This simplified statistical analysis by allowing the use of arithmetic operations (SWM are rated on a logarithmic scale) and enabled the use of the measured force values of the filaments determined during calibration (shown in Table 1). In order to assign a numerical value to the sensitivity of a location, the force corresponding to the thinnest monofilament that generated a positive response was generally scored. Usually, when a monofilament was sensed at a site, all higher levels of the monofilament were also sensed at that site (see Figure 3.2).

Figure 3.2: Example of a common observation for the heel. The site was not felt at the first three levels, and was first felt at 3.84. The heel location is therefore scored at 0.42 grams, the calibrated force corresponding to the 3.84 monofilament.



In some cases (16% of total measurements) a monofilament was sensed at a lower level but not felt at a higher level. In these cases it was decided that recording the lowest sensed filament level while ignoring the fact that a subsequent filament was not sensed could result in an underestimation of the sensitivity threshold. On the other hand, recording the first filament sensed after the "gap" could overestimate the sensitivity threshold. To address this problem, when a gap occurred between sensed filament levels, the sensitivity threshold recorded was increased from the lowest level felt. If the gap consisted of one level, then the recorded threshold was increased by one filament level, and if the gap contained two filament levels, the threshold was increased by two levels. Figure 3.3 demonstrates this scoring system.

Figure 3.3: Example of an observation for the heel in which a filament is sensed at a lower level, and missed at the next higher level. Scoring is adjusted by increasing the lowest sensitivity felt (3.22) by the number of levels missed (in this case, one) thus the force corresponding to filament level 3.61 is scored.

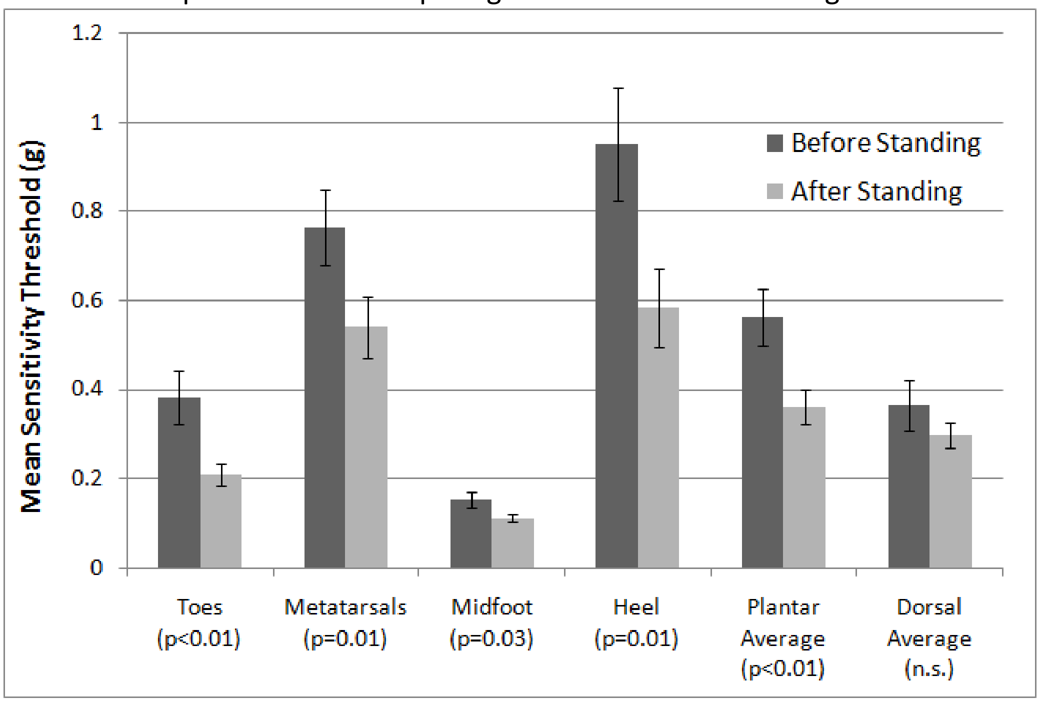
After values for individual testing sites were determined, data from physiologically similar locations were combined into five regions in order to more easily compare different areas of the foot. The hallux, third, and fifth toe testing sites were averaged (toes), as were the sites under the first, third, and fifth metatarsal heads (metatarsals). Data from the four dorsal sites were averaged (dorsal), while the “heel” and “midfoot” sites were analyzed as single locations. In addition, a “plantar average” was calculated by taking the mean of the four plantar regions (toes, metatarsals, midfoot, and heel). Paired t-tests were performed to compare the sensitivity values before and after prolonged standing for each region and for the plantar average.

Results

The paired t-test of plantar sensitivity showed that four hours of standing significantly lowered the force threshold for sensing a monofilament for all plantar sites ($p < 0.05$). There was however no evidence of a significant change in the sensitivity threshold of the dorsal surface of the foot ($p = 0.12$). Means and standard errors for sensitivity thresholds before and after four hours of standing are shown in Figure 3.4. The mean decrease in average plantar sensitivity threshold was 0.20 grams ($p < 0.01$)

from 0.56 before standing to 0.36 grams after standing. The heel and metatarsals showed the largest decrease in threshold, with differences of 0.37 (p = 0.01) and 0.22 (p = 0.01) grams respectively, while the midfoot demonstrated the lowest decrease, 0.04 grams (p = 0.03).

Figure 3.4: Mean Sensitivity thresholds (grams-force) before and after four hours of standing for regions of the foot. Error bars represent standard error of the mean. P-values are for paired t-tests comparing before and after standing.



Discussion

To our knowledge, the increased plantar sensitivity (i.e., the decreased thresholds) after prolonged standing is previously undocumented. This finding may have implications for interpreting results of diabetic neuropathy testing (Valk, 1997; Armstrong, 1998). More research is necessary to accurately quantify this phenomenon with respect to duration of standing time, to investigate whether diabetic populations are also affected, and to understand the underlying cause of the sensitivity changes.

Limitations

This study measured changes in touch sensitivity of the foot over several replications while controlling for footwear and activity during prolonged standing. However, this research was a pilot study as part of a larger experiment, and sought merely to establish whether prolonged standing affects changes in plantar touch sensitivity. The experiment included only young, healthy subjects, so future experimentation will be necessary to determine if these findings extend to older populations and diabetic patients at risk for peripheral neuropathy. This experiment also exposed subjects exclusively to standing. It is unknown whether similar results could be observed for prolonged periods of walking, or mixed standing and walking.

While subjects were encouraged not to stand or walk for long periods before the experiment, their activity prior to each experimental session was not standardized, nor was footwear worn prior to the experiment. Testing sites were not marked by the investigators, so it is possible that there was some variation in testing location for each site.

This experiment on its own is insufficient to explain the mechanism for change in sensitivity, but these results suggest that the primary cause may be tissue compression, possibly resulting in hyperalgesia. While all plantar surfaces demonstrated significant change in sensitivity, the dorsal surface, presumably subject to very little compression, did not show significant change.

Venous pooling in the legs is a condition which may cause a change in sensitivity (Padberg, 1999), but if this were the case a significant change would have been expected for the dorsal surface in addition to the plantar locations. The effects of skin temperature and moisture could not be ruled out by this study. Skin temperature has been shown to affect sensitivity (Gescheider, 1997), and skin moisture may affect sensitivity by altering the mechanical properties of the skin (Jemec, 1990). This experiment was conducted in a climate-controlled laboratory, but skin temperature and moisture were not measured at the time of testing. These effects are likely small since the dorsal aspect of the foot did not demonstrate significant sensitivity changes with prolonged standing and would presumably experience similar moisture and temperature. However, moisture and temperature differences may have been possible due to the mesh fabric top of the shoes, which may have allowed evaporation.

Future Work

To identify the causes of change in plantar sensitivity, future studies should measure the skin temperature and moisture of the feet when measuring touch sensitivity. If sustained tissue compression is indeed the primary cause of change in sensitivity, measures of changes in skin stiffness and fat pad thicknesses may also help to identify the underlying mechanics for this sensitivity change. Future research should also control for activity and footwear used prior to the experiment. Finally, touch sensitivity should be measured more frequently during and after standing to determine the onset and recovery times for sensitivity changes. This will provide physicians with a potential corrective factor for SWM testing of patients who have been standing.

Implications for Clinical Practice

The greatest change in sensitivity threshold occurred at the heel, where the mean sensitivity threshold dropped from 0.95 to 0.58 grams after standing. A 0.95 gram-force corresponds very nearly to the 4.08 filament level, while 0.58 grams is nearly equal to the 3.84 filament (see Table 1). Therefore this change equates to reduction in threshold of approximately one filament level. Using the approach just described, sensitivity threshold changes were computed in terms of filament levels for all locations. However, interpolation was used to make exact conversions since beginning and ending threshold forces were never exactly equal to specified filament levels. Thresholds were reduced an equivalent of 0.9 filament levels for the toes, 0.8 for the metatarsals, 0.4 for the midfoot, 1.0 for the heel, and 1.0 levels for the plantar average.

Inability to sense a SWM level of 5.07 (10 grams) is a clinically accepted indicator of risk for foot ulceration in diabetic patients (McNeely, 1995). The results of this experiment suggest that touch sensitivity testing may result in a false negative finding if the patient is tested after having spent a prolonged time on his or her feet. This standing may result in a reduction of sensitivity threshold and the patient may be thought to have normal sensation when their sensation is in fact impaired. If these same results are observed in diabetic patients, this might require testing patients who have been standing for extended periods with a different filament, such as the 4.93 (8 gram) which is one level below the 5.07. Further research into the temporal variability of touch sensitivity with respect to postural activities will be useful for developing modifications to testing procedures to address potential unintended bias in clinical touch sensitivity testing.

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CHAPTER IV

Local Sensitivity to Constant Pressure Applied to Different Regions of the Plantar Foot

Abstract

Objective: To investigate the effect of plantar pressure on pain thresholds for constant levels of pressure common during standing.

Background: The mechanisms that cause foot discomfort during prolonged standing are poorly understood. The relationship between plantar pressure and discomfort has received little investigation, and no studies have examined the effects of low levels of constant pressure typical during standing.

Method: Pain thresholds were measured for 20 healthy participants by applying five levels of constant pressure at different locations on the foot using a 1 cm^2 circular probe. A survival analysis was performed to determine the effects of pressure and foot location on the time until pain onset. In an additional experiment, participants located the origin of pain while standing on surfaces of different hardness, and the effects of peak plantar pressure and pressure distribution on pain were determined.

Results: Time to pain threshold was significantly affected by pressure ($P < 0.001$); time decreased as pressure level increased. Foot location was also significant ($P < 0.001$), with the greatest time to pain (least sensitive) observed under the heel and fifth metatarsal head, and the shortest times (most sensitive) found under the midfoot. During standing, pain originated primarily at the heel and first metatarsal head, regions corresponding to the greatest plantar pressures. Softer surfaces significantly reduced peak pressure and pain.

Conclusion: Discomfort during standing can be reduced by limiting total pressure under the midfoot and reducing high localized pressure concentrations. Softer surfaces appear to reduce discomfort by reducing peak pressures at the heel and metatarsals.

Introduction

Prolonged standing is a daily requirement for many workers (Tissot, 2005) and has been linked to discomfort and fatigue in the lower limbs (e.g., Cham, 2001; Madeleine, 1998). Altering the flooring surface with "anti-fatigue" mats has been shown to reduce discomfort when compared to standing on hard flooring (e.g., Redfern, 1995; Madeleine, 1998; Cham, 2001), but the reason is still unclear why a particular floor surface is more comfortable than others. Like mats, shoe inserts have been shown to effectively mitigate discomfort (Cham, 2001; King, 2002), but there is no agreement on which designs for mats and shoe inserts are most effective. In order to select interventions such as mats and inserts that enhance comfort during standing, a better understanding is needed of the mechanisms that cause discomfort.

There is substantial physiological evidence suggesting that pressure on the plantar (bottom) surface of the foot may be a mechanism for discomfort. 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, 1967; Silvino, 1980). In static, barefoot standing, plantar pressures on the foot average about 70 kPa, with peaks of around 140 to 175 kPa (Cavanagh, 1987; Wiggermann, 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, 1958; Dinsdale, 1974), and have been shown to cause nerve impairment in rabbits (Rydevik, 1981). Extended exposure to pressure above 15-20 kPa interrupts arterial blood flow and causes cell death in canines (Hargens, 1981).

Very little research has investigated the relationship between plantar foot pressure and discomfort (Rolke, 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, 1993). PPT has been studied in the second toe (Brennum, 1989) and the abductor hallucis of the arch of the foot (Rolke, 2005), but the only study to evaluate the PPT at multiple locations on the foot was Messing (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).

While 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 (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, 1987). The steadily-increasing pressure applied in PPT tests is also not representative of the relatively constant 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, 1986). This suggests that traditional PPT testing may not accurately measure the effect of *static* pressures on pain.

The primary objective of this research was to investigate the effect of plantar pressure on pain threshold by introducing a pain-pressure threshold test at constant pressure (PPT-CP) that uses levels of pressure common during standing to the heel and metatarsal heads. It was hypothesized that 1) PPT-CP (measured as the time to pain onset) decreases as the magnitude of constant 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.

Methods

The primary emphasis of this experiment was a pain-pressure threshold test in which a constant pressure was 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.

Participants

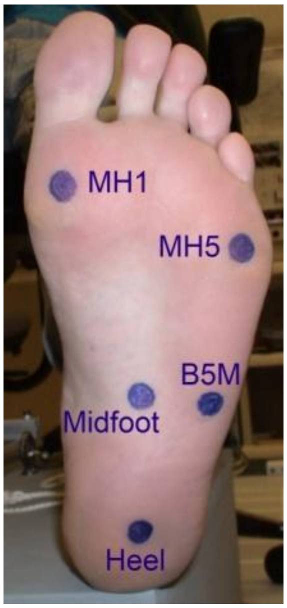
20 healthy participants (10 male, 10 female) with no history of lower extremity disorders were recruited from a student population. The mean age of participants was 21.2 years (SD, 2.5 years), and mean body mass was 70.0 kg (SD, 10.3 kg). To ensure that foot geometry (e.g., underlying bone location, 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 for this experiment were approved by the University of Michigan Institutional Review Board. All testing was performed in a laboratory at the University of Michigan.

Pain-Pressure Threshold with Constant Pressure (PPT-CP)

The PPT-CP 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 PPT-CP 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). One pressure level was replicated, so there were 30 total trials (5+1 pressure levels x 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. Figure 4.1 illustrates the test locations.

Figure 4.1: Test locations on the foot for the PPT-CP.



During PPT-CP 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, 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 three-second 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 PPT-CP was determined 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 seconds, the trial was ended. Pilot testing showed that when pain was not reached within the first 180 seconds, the sensation of pain could take a 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 (VAS).

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, 2005), PPT-CP 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 before moving to the opposite foot, alternating between the feet 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. 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 seconds), or observations in which the participant immediately indicated pain. The level replicated was the lowest level for which PPT-CP was uncensored for at least four of the foot locations.

A survival analysis (Kaplan, 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 PPT-CP of trials performed earlier in the experimental session were compared to their subsequent replications using a repeated measures ANOVA. A repeated measures ANOVA was also performed to test whether discomfort ratings were influenced by pressure level and foot location.

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. 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 Figure 4.2. The same definition of pain was used as for the PPT-CP test. F-Scan® pressure sensors (Tekscan; Boston, MA, USA) were taped to the feet to record pressure while standing. 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.

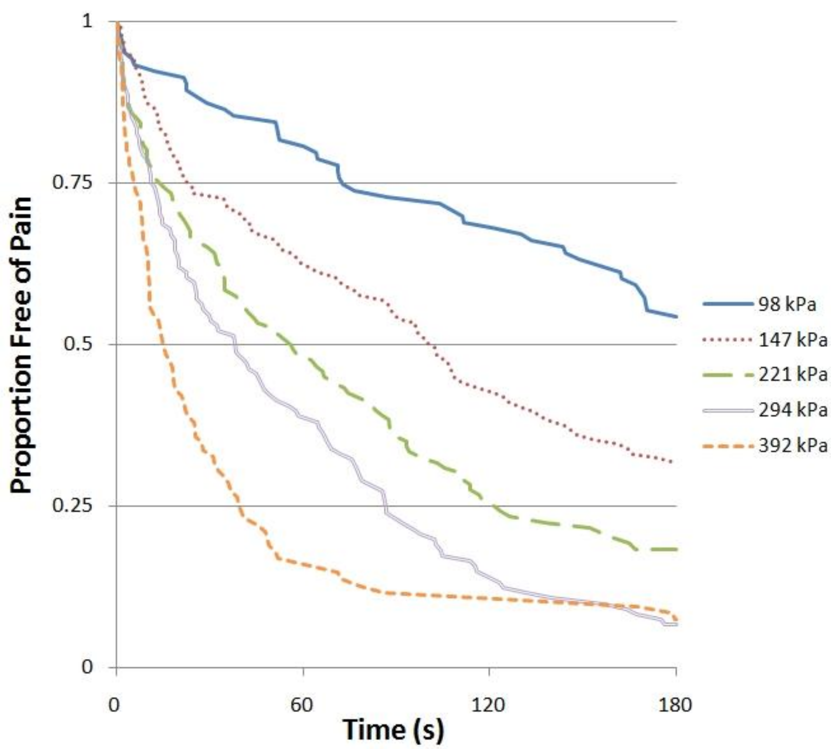
Figure 4.2: Diagram used by the participants to indicate the location of the onset of pain when standing.

Results

Pain-Pressure Threshold with Constant Pressure (PPT-CP)

The PPT-CP time 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. Figure 4.3 shows "survival curves" for each pressure level.

Figure 4.3: Survival curves for all trials at each pressure level. The curves show the proportion of the participants not reporting pain versus time.



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 ($P < 0.05$). Figures 4.4, 4.5, and 4.6 show survival curves for each foot location at selected pressure levels. Figure 4.4 shows that at the lowest pressure level (98 kPa), most of the participants had not reached pain after 180 seconds in nearly all foot locations except in the midfoot, where 50% had reported pain after about 70 seconds. Figure 4.5 illustrates that at the third pressure level (221 kPa), the fifth metatarsal was least sensitive to pressure, with 50% reporting pain after approximately 120 seconds. Again, the midfoot was most sensitive to pressure, with 50% having reported pain after 50 seconds, and no participants lasting longer than 120 seconds. At the greatest pressure level (392 kPa) shown in Figure 4.6, more than 50% of the participants reported pain after 30 seconds for all locations, and more than 75% reported pain after 70 seconds. Again, the midfoot was most sensitive to pressure, with all participants reporting pain after 20 seconds of applied pressure.

Figure 4.4: Survival curves at pressure level 1 (98 kPa) for all tested foot locations. Note that the midfoot is more sensitive than other locations.

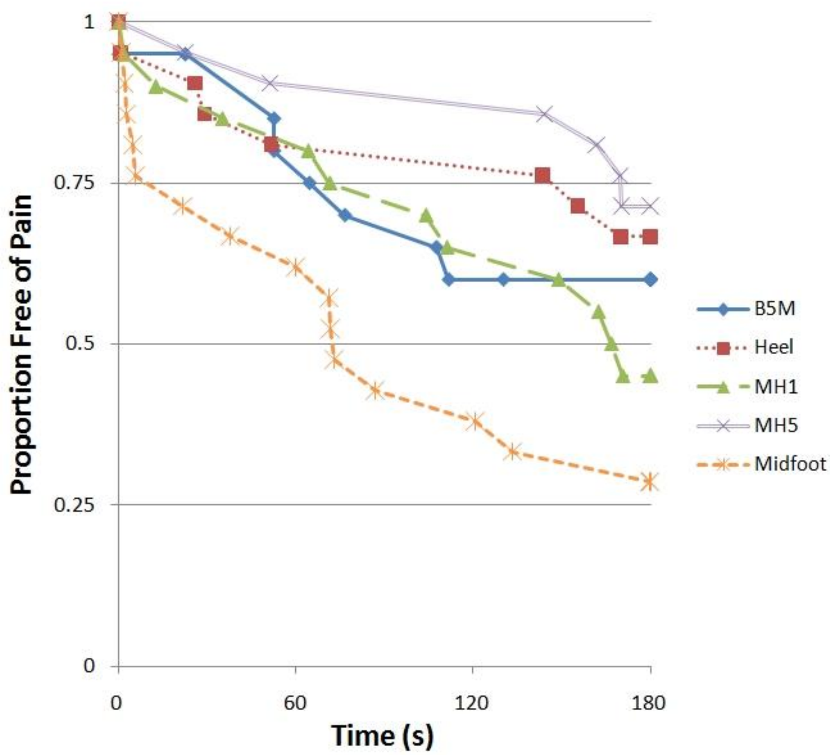


Figure 4.5: Survival curves at pressure level 3 (221 kPa) for all tested foot locations. Slopes are substantially steeper than observed for pressure level 1, and the midfoot continues to be the most sensitive.

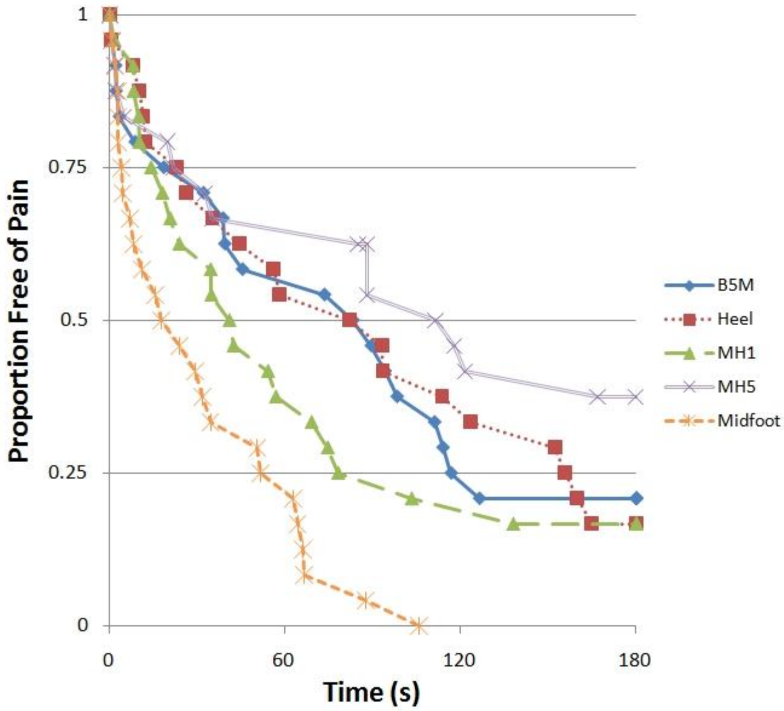
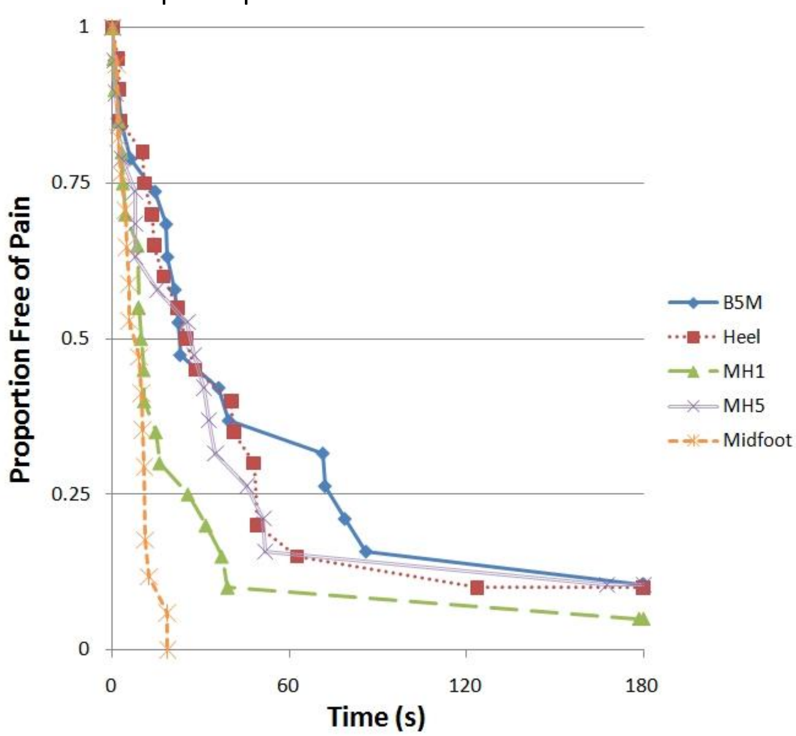


Figure 4.6: Survival curves at pressure level 5 (392 kPa) for all tested foot locations. Note that all participants terminated the trial in less than 30 seconds at the midfoot.



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, as it included some censored data (29 of 192 observations).

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 ($P < 0.001$).

Standing Pain Threshold Location

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 Figure 4.7). In comparison, pain onset was identified at the heel in 47% of trials, and at the metatarsal heads in 52% of trials (see Figure 4.8). 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.

Figure 4.7: Location of peak pressure for all trials. * indicates five peak pressures in the same location.

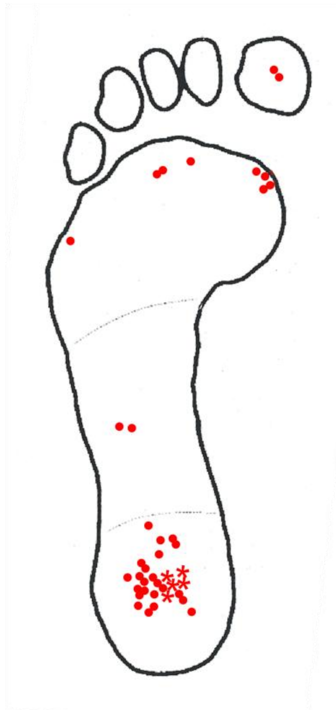
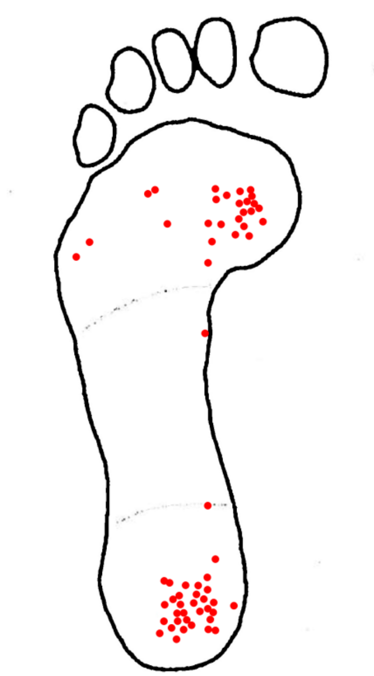


Figure 4.8: Location of pain onset for all trials.



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%).

Discussion

This study was the first to evaluate the relationship between the 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 PPT-CP test, our findings are generally consistent with Messing (2001) who found the lowest threshold for pain at the midfoot. However, Messing found the heel to have higher thresholds than all other locations, while 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 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, 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, 1993).

Despite instructions to identify the pain threshold as the same sensation across all trials, the discomfort ratings taken after each trial increased with pressure level and were higher for the midfoot. A possible explanation for this result is 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 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, 2000). The resulting inflammation increases pain and discomfort (Cervero, 2003).

The PPT-CP 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 this discrepancy may be accounted for by sensitivity differences dependent on foot location. For example, Figure 4.8 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, 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, 2003). It is also possible that when standing, tension in muscles and ligaments (Hutton, 1991) and shear stresses (Bennett, 1979) occur that also contribute to pain. These mechanisms for discomfort may account for the discrepancy between the location of peak pressure and pain.

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. While the PPT-CP results showed that the midfoot is most sensitive to pressure, the benefits of softer surfaces in reducing peak pressure must 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 PPT-CP 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. While the PPT-CP 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.

Plantar Pressure and Weight-Shifting

Despite several attempts, this study was unable to establish a connection between plantar pressure and weight-shifting (Chapter 2). Such a connection between weight-shifting and a physiological mechanism for discomfort (i.e., plantar pressure), would have further established weight-shifting as a proxy measurement for discomfort.

Several approaches were attempted to study the effect of plantar pressure on weight-shifting while introducing as few artificial conditions as possible. In one attempt, participants stood in an anti-gravity treadmill (Alter-G; Fremont, CA, USA) which works by pressurizing a chamber around the legs of the user, causing air pressure to lift the person upward. This upward force resulted in reduced plantar pressure, but the physical constraints of device prevented participants from shifting their weight normally. In another attempt, holes were drilled in particle board to reduce the surface area of the surface in contact with the foot, thereby increasing peak plantar pressures. Again, participants did not shift their weight normally. Some participants reported that when standing on the surface with holes they avoided shifting weight because lifting the foot temporarily increased pain rather than providing relief. In a final attempt to link plantar pressure and weight-shifting, participants were asked to stand for ten minutes on surfaces of varying hardness. Again, higher peak pressures did not correspond to an increase in weight-shifting, possibly because discomfort differences between surfaces took longer to emerge, or because participants altered their behavior because they were conscious that the pressures under their feet were being recorded. Regardless, this research was not able to establish a connection between plantar pressure and weight-shifting, presumably because of artifacts that could not be avoided when manipulating plantar pressure.

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). Finally, exploring the cause of variation in discomfort ratings measured after the PPT-CP 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.

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.

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. Finally, while peak pressure seems to be a good predictor of discomfort in the foot, there appear to be other mechanisms affecting discomfort that are unknown.

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CHAPTER V

Effect of Flooring and Footwear on Plantar Pressures During Standing and Walking in Healthy Young Adults

Abstract

Background: Elevated plantar pressures are associated with pain and ulceration of the foot. Few studies have examined the effect of flooring on plantar pressures, and none have studied the effect of “anti-fatigue” mats, which are common in work environments that require prolonged standing.

Methods: Plantar pressures were measured in 10 healthy young adults, both barefoot and wearing shoes, as they stood and walked on a hard surface and two mats. The effects of flooring and footwear on plantar pressures were evaluated in separate repeated measures analyses of variance using a p value of 0.05.

Findings: For barefoot standing and walking, harder flooring caused increased peak pressures ($P < 0.001$) by up to 35% (standing) and 44% (walking) when compared to more compliant flooring, but flooring had only a very small effect (less than 3% of mean values) when shoes were worn. Compared to walking barefoot, shod walking decreased peak pressures ($P < 0.001$) by 44%, but increased ground reaction forces on the feet by 22%.

Interpretation: The results for standing and walking suggest that flooring has little effect on plantar pressures when shoes are worn. When compared to walking barefoot, shoes decrease peak pressure. The finding that walking with shoes increases ground reaction forces as compared to barefoot walking requires further investigation, and suggests that shoes may have mixed benefits for reducing pressure during walking.

Introduction

Elevated pressures on the plantar surface of the foot have been associated with negative health outcomes. High levels of plantar pressure have been linked to foot pain (Burns, 2005) and metatarsalgia (Silvino, 1980). In individuals with diabetic peripheral neuropathy, elevated plantar pressures are associated with ulceration (Frykberg, 1998; Sacco, 2009). Higher levels of plantar pressure during walking have also been identified in older adults with a history of falling (Mickle, 2010). There seems to be a consensus that any product such as footwear (e.g., Bartlett, 1995; Yung-Hui, 2005), insoles (Chen, 1994; Shiba, 1995), or hosiery (Veves, 1989) that is capable of reducing plantar pressure is desirable.

Many studies have compared barefoot and shod walking to investigate the effect of wearing shoes on plantar pressures (Soames, 1985; Sarnow, 1994; Perry, 1995; Nyska, 1995; Burnfield, 2004; Mohamed, 2005; Molloy, 2009). These studies all generally found a decrease in peak pressures when shoes are worn. However, when evaluating pressures over the entire foot such as ground reaction forces (GRF) and the pressure-time integral (PTI), results differed across studies. Nyska (1995) found an overall 41% decrease in PTIs on the foot when shoes were worn as compared to barefoot walking. In constrast, Soames (1985) found both increases and decreases in PTI depending on foot location, and Sarnow (1994) found no change in GRFs on the foot.

While many have studied the effect of footwear on plantar pressures, the effect of flooring on plantar pressure has been given relatively little attention. The role of flooring in plantar pressures may be particularly important for employees in retail (Ryan, 1989), health care (Meijsen, 2007), and manufacturing (Keyserling, 2010) who often stand for prolonged periods. In these environments, “anti-fatigue” mats are frequently placed on top of hard floors like concrete to reduce discomfort associated with prolonged standing (Cham, 2001). Mohamed (2005) found elevated plantar pressures when walking barefoot on concrete when compared to walking on grass or carpet, but did not find differences when shoes were worn. Finlay (2007) placed a pressure-sensitive mat underneath different carpeted surfaces to measure gait characteristics as participants walked with shoes, and did not conclude that flooring affected plantar pressures. The effect of anti-fatigue mats on plantar pressure has not been studied during walking, and the effect of flooring of any kind on plantar pressure has not been studied when standing.

The main objective of this experiment was to determine whether anti-fatigue mats reduce plantar pressures for standing and walking in both barefoot and shod conditions. The null hypothesis was that mats do not reduce peak pressures for walking or standing when barefoot or shod. The secondary objective was to determine the effect of footwear on plantar pressures, with the null hypothesis that shoes do not reduce plantar pressures during standing and walking.

Methods

Participants stood and walked on three different surfaces under both barefoot and shod conditions. Pressures were measured using in-shoe pressure sensors that were taped to the plantar surface of the foot during all trials.

Participants

Ten healthy participants (five male, five female) were recruited from a student population. Participants reported that they had no history of back pain, lower extremity disorders, and were not pregnant. The mean age of participants was 23.5 years (SD, 3.8 years), and mean body mass was 70.3 kg (SD, 14.9 kg). Shoe sizes ranged from US size 8.5 to 11 for men and 6.5 to 9 for women. All participants provided written informed consent, and methods for this experiment were approved by the University of Michigan Institutional Review Board. All testing was performed in a laboratory at the University of Michigan.

Equipment and Instrumentation

Plantar foot pressures were collected using the F-Scan® system (Tekscan; Boston, MA, USA). The F-Scan sensors are 0.13 mm thick and composed of a grid of 0.51 x 0.51 cm sensor elements that measure pressure by electrical resistance. Prior to data collection, F-Scan sensors were trimmed to fit participants' shoes, and were adhered to the feet using double-sided Scotch® tape (3M Company; St. Paul, MN, USA).

Participants stood and walked on two mats and a hard control surface during the experiment. The "harder mat" was 0.95 cm thick, and composed of a thin, hard rubber top layer with a dense foam rubber backing. The "softer mat" was 1.59 cm thick, and composed of a moderately hard vinyl surface with a thick, soft foam rubber backing. Appendix A describes in detail the material properties of these mats. The hard control surface for walking was linoleum tile on a concrete floor, and for standing was a hard acrylic plastic. For the shod portions of the study, participants wore the same brand and model of athletic shoe (Gel Kanbarra 5; Asics®; Irvine, CA, USA). Appendix B describes the results of material testing performed on these shoes.

Standing

The standing portion of the study was a full-factorial design, in which participants stood for 90 seconds in every combination of three factors: flooring (softer mat, harder mat, and hard acrylic plastic), stance (balanced and predominantly single foot weight-bearing), and footwear (shod and barefoot). Each condition was replicated twice resulting in a total of 24 standing trials (3 floors X 2 stances X 2 footwear conditions X 2 replications). For the two replications for the single foot weight-bearing stance, a single trial was performed for each of the right and left foot. Because it was difficult to remove the shoe and ensure that the sensors remained taped to the foot, all barefoot standing trials were run together, followed by all shod standing trials. Within barefoot and shod conditions, trials were run in a randomized order. After each 90-second standing trial, participants took 60 seconds of seated rest.

Before the standing trials, the participant was asked to select a comfortable bipedal stance, spacing their feet as they preferred. A fixture was then adjusted that touched against the heels and the lateral face of the fifth metatarsal. (See Figure 5.1). The position of the fixture was held constant across all trials to allow the participant to consistently locate their feet. The test flooring conditions were placed on two adjacent force plates (AMTI; Newton, MA, USA), and the participant stood with one foot over each force plate. The force plates were used to provide visual feedback to the participant regarding the relative weight supported by each foot. In the balanced stance, participants were instructed to stand with 50% of body weight on each foot. In the predominantly single foot weight bearing stance, participants stood with 94% of body weight on one foot, and participants were permitted to lift the heel of the off-loaded foot if desired. These two stances were chosen because a previous study showed that even balance and 94% load on one foot were preferred loading distributions during prolonged standing (Wiggermann, 2010). Participants were generally able to maintain the weight distribution between the feet within 1% of the target for the given stance. In a few circumstances (less than 2% of trials) a trial was repeated when balance was lost and a participant swayed more than 5% from the target balance distribution.

Figure 5.1: Experimental setup.

In-shoe pressure data were collected at a sampling frequency of 20 Hz, and a point calibration was applied to each standing trial, as recommended by the manufacturer. Using the F-Scan software, each data file was carefully inspected for errant readings caused by a wrinkle in the sensor or a defective sensor element. When an errant sensor element was found, the value for the element was recalculated as the average of all adjacent elements for the entire data file. These data were then saved as ASCII files and the average peak pressure for each trial was then computed using custom a program written in Matlab®. Average peak pressure was defined as the mean of the greatest level of pressure on the foot for each sample during the entire 90 seconds of standing. Each combination of footwear and stance (barefoot-single, barefoot-balanced, shod-single, shod-balanced) were analyzed in a repeated measures analyses of covariance, and the effect of participant, flooring, stance, and foot (i.e., left, right) was tested on peak pressure. The anterior-posterior location of the center of pressure was included as a potential covariate. A separate analysis of covariance was also performed that collected all trials and tested for the effect of footwear (barefoot vs. shod) on peak pressure. A post-hoc power calculation was performed to estimate the size of the difference likely to be detected by this experiment. With the sample size and variance observed, this study had a power of 0.90 to detect a difference of 13 kPa or more between surfaces.

Walking

The walking portion of the study immediately followed the standing portion of the experiment. Before the walking trials, F-Scan sensors were calibrated using the step calibration procedure in the F-Scan data acquisition software. Participants walked six times on ten-meter lengths of each of the three surfaces (softer mat, harder mat, and linoleum tile on concrete floor). All shod walking trials were run together, followed by all barefoot trials. Within barefoot and shod conditions, trials were run in a randomized order.

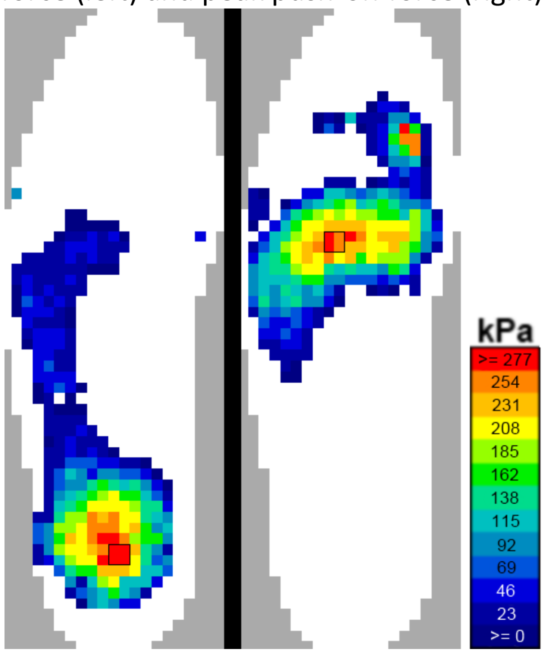
Participants walked in time with a metronome that sounded at 100 beats per minute (Latt, 2008) while in-shoe pressure data were recorded at a frequency of 300 Hz. To assist with analysis of pressure data, video was recorded that was synchronized to the pressure recordings. For each walking trial, the first and final three steps were excluded from analysis. A custom program was written in Matlab® (MathWorks; Natick, MA, USA) to compute gait characteristics for each step. *Peak pressure* was defined as the greatest pressure observed at any 0.51 x 0.51 cm sensor element during stance phase of gait. Total contact time (t_c) was also measured for each step. The calculation of *Peak Rear Foot Ground Reaction Force* (GRF_{RF}) and *Peak Push-Off Force* (GRF_{PO}) is shown by equations 1 and 2.

$$\mathrm{GRF}_{RF} = \sum P_{HS} * (2.6 * 10^{-5}\ \mathrm{m}^2) \qquad \text{(Equation 1)}$$

$$\mathrm{GRF}_{PO} = \sum P_{TO} * (2.6 * 10^{-5}\ \mathrm{m}^2) \qquad \text{(Equation 2)}$$

$\sum P_{HS}$ is the sum of the pressures for all sensor elements at the moment associated with peak GRF. 2.6×10^{-5} m^2 is the area of each element. Figure 5.2 shows a graphical output from the F-Scan software that represents a typical pressure distribution at the moment of heel strike and toe off.

Figure 5.2: Typical pressure recording measured for the peak rear foot ground reaction force (left) and peak push-off force (right)



The calculation of *Pressure-Time Integral (PTI)* is shown by the equation 3:

$$PTI_{i,j} = \frac{\left(\frac{\sum_{1}^{300t_{c_j}} P_k}{A_i}\right)}{300t_{c_j}} \quad \text{(Equation 3)}$$

$PTI_{i,j}$ is the pressure-time integral for participant *i,* step *j*. $\sum P_k$ represents sum of all pressures for all sensor elements measured during all samples (*k*) of step *j*. A_i is the contact area, a constant determined for each participant *i*, defined as the greatest number of sensor elements returning a non-zero value across all steps taken by the participant. t_c is the contact time (in seconds), and 300 is the sampling rate.

Shod and barefoot trials were tested in separate repeated measures analyses of variance. The effect of participant, flooring, stance, and foot (i.e., left, right) on Peak Pressure, GRF_{RF}, GRF_{PO}, PTI, and t_c were determined. Another separate analysis of variance was performed to test for the effect of footwear on Peak Pressure, GRF_{RF}, GRF_{PO}, PTI, and t_c. Four participants were unable to complete the walking trials in the barefoot condition because the tape on the sensors failed to hold. Therefore, only the six participants that completed both barefoot and shod walking trials were included in the analysis comparing footwear.

Results

Standing

When standing barefoot, flooring had a significant effect on peak pressure in both balanced and predominantly single foot weight-bearing stances ($P < 0.001$ for both stances), so the null hypothesis that mats do not reduce peak pressure was rejected. Pairwise comparisons showed significant differences in peak pressure across all three surfaces. As shown in Figure 5.3, in balanced standing the hard control surface resulted in the greatest peak pressure (mean 176 kPa, SD 32 kPa), the softer mat resulted in the least (114 kPa, SD 22 kPa), and the harder mat was in between (154 kPa, SD 26). When shoes were worn, flooring did not have a significant effect on peak pressures, and the null hypothesis was not rejected. The same trend was observed in the predominantly single foot weight-bearing stance, with the greatest peak pressure on the hard control (mean 242 kPa, SD 54 kPa), the least on the softer mat (158 kPa, SD 31 kPa), and the harder mat in between (198 kPa, SD 29 kPa). Again, when shoes were worn flooring did not have a significant effect on peak pressures for single foot weight-bearing (see Figure 5.4).

Figure 5.3: Mean peak pressures for each flooring and footwear condition for standing in balanced stance. Error bars represent standard error of the mean. *Significant difference in pairwise comparison.

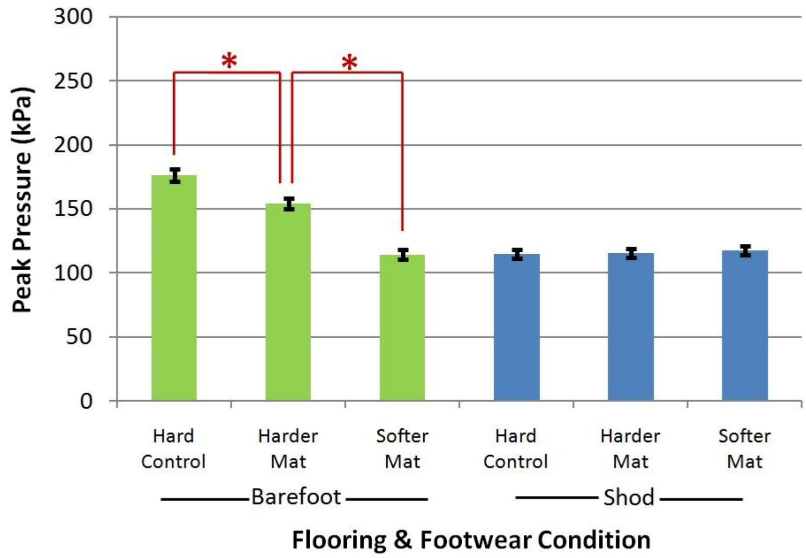
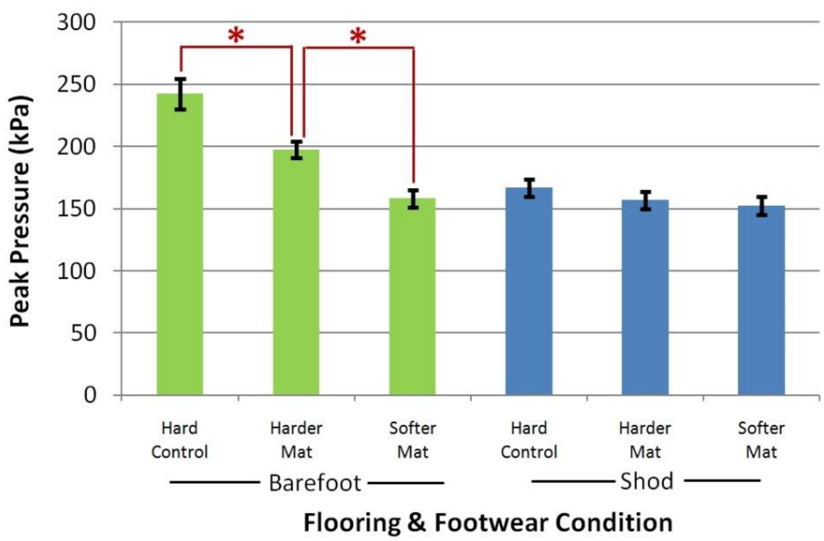


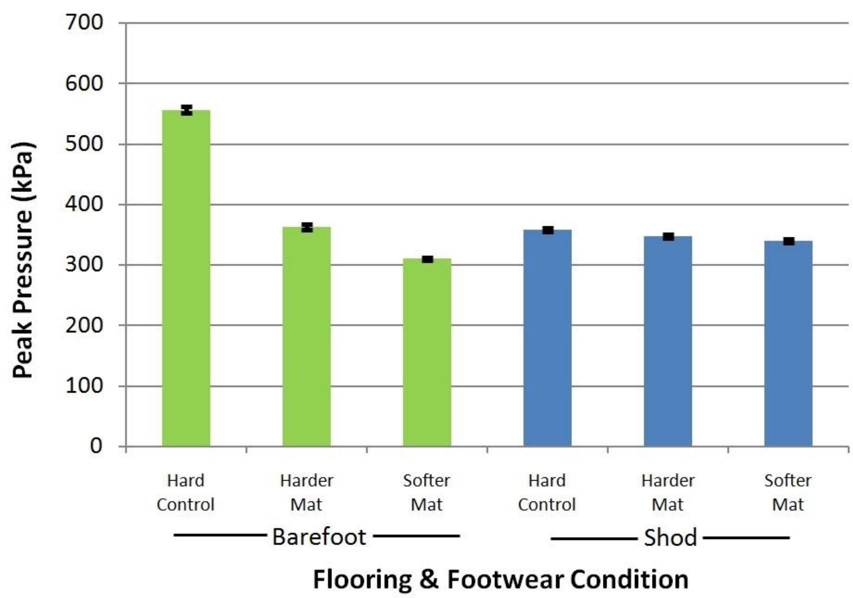
Figure 5.4: Mean peak pressures for each flooring and footwear condition for standing with body weight primarily on one foot. Error bars represent standard error of the mean. *Significant difference in pairwise comparison.



Walking

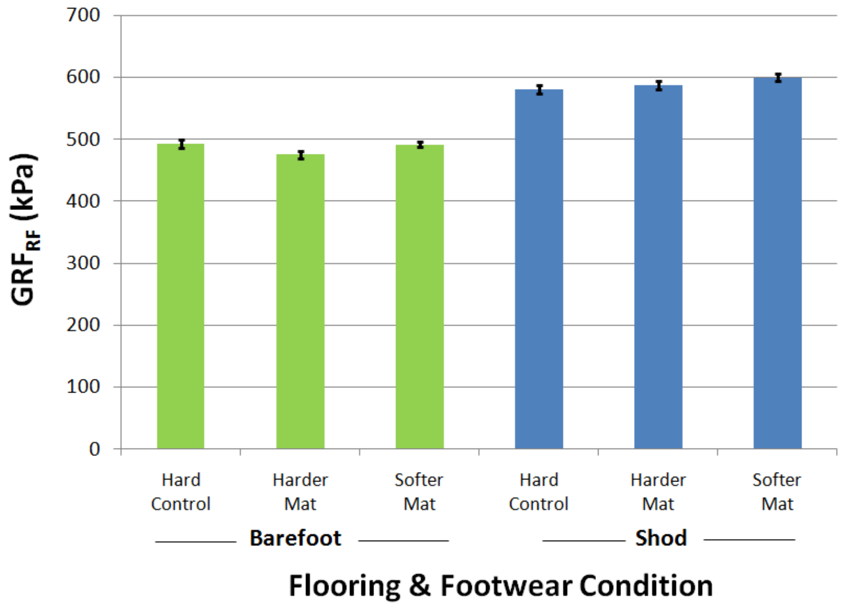
Flooring had a significant effect on peak pressure during walking ($P < 0.001$), with the hard control surface being associated with the greatest peak pressures, so the null hypothesis that mats do not reduce peak pressures was rejected. This effect was especially pronounced in the barefoot condition (see Figure 5.5) where the hard control showed a mean peak pressure of 557 kPa (SD 85 kPa), the harder mat resulted in 363 kPa (SD 76 kPa) and the softest mat 310 kPa (SD 49 kPa). Flooring significantly affected peak pressure when shoes were worn ($P < 0.001$), but the effect size was small. When shod, mean peak pressures were 358 kPa (SD 56 kPa) for the hard control, 347 kPa (SD 53 kPa) for the harder mat, and 340 kPa (SD 45 kPa) for the softer mat. Peak pressures for each of the shod conditions were significantly lower ($P < 0.001$) than for barefoot on the harder mat, and greater ($P < 0.001$) than for barefoot on the softer mat.

Figure 5.5: Peak pressures for each flooring and footwear condition during gait. Error bars represent standard error of the mean. Within barefoot and shod conditions, all pairwise comparisons are significant.



The effect of flooring on GRF_{RF} and GRF_{PO} was significant for both barefoot ($P < 0.001$) and shod ($P < 0.05$) conditions, but the effect size was very small (less than 3% of mean values). However, wearing shoes increased GRF_{RF} by 21% (95% confidence interval 19 to 23%) and GRF_{PO} by 24% (C.I.: 22 to26%). Figure 5.6 shows the GRF_{RF} for each flooring and footwear condition; similar trends were observed for GRF_{PO} and PTI. The effect of flooring on PTI was significant for both barefoot ($P < 0.001$) and shod ($P < 0.05$) conditions. Again the effect size was very small (less than 1% of the mean for shod conditions, less than 4% of the mean for barefoot conditions), and wearing shoes increased PTI by a mean of 28% (C.I.: 22 to 32%). Flooring did not have a significant effect on t_c.

Figure 5.6: Peak push-off force (GRF_{RF}) on the foot for each flooring and footwear condition during gait. Error bars represent standard error of the mean.



Discussion

When standing and walking in barefoot conditions, harder flooring caused an increase in peak pressures as compared to softer flooring, but flooring had little effect when shoes were worn. Walking with shoes caused an increase in ground reaction forces (GRF_{RF}, GRF_{PO}, and PTI) as compared to barefoot walking.

Standing

This is the first study to investigate the effect of flooring on plantar pressures during standing. The results suggest that wearing soft-soled athletic shoes is a suitable means for reducing peak plantar pressures while standing. When shoes are not worn, soft flooring is also a method for reducing peak plantar pressures. As compared to barefoot standing on hard flooring, shoes and soft flooring when barefoot appear to reduce peak pressures by redistributing pressure over a larger contact area. These findings may be particularly important to individuals with diabetes, for whom elevated peak pressures have been associated with increased risk of ulceration (Frykberg, 1998; Sacco, 2009), suggesting that these individuals wear shoes whenever possible.

Walking

During walking, flooring only affected peak pressure during barefoot conditions. Flooring had no meaningful effect on peak pressures when shod, or for ground reaction forces (GRF_{RF}, GRF_{PO}, or PTI) in both barefoot and shod conditions. These findings are consistent with Finlay (2007) who did not conclude that flooring resulted in differences in plantar pressures during shod walking. Our results corroborate Mohamed (2005) who identified an increase in peak pressures during barefoot walking on concrete as opposed to carpet and grass. However, Mohamed et al. found a much larger increase in PTI for barefoot walking on concrete than the current study.

A 38% reduction in peak pressures was observed when walking with shoes as compared to barefoot, which is in agreement with previous studies that compared plantar pressures during barefoot and shod walking (Soames, 1985; Sarnow, 1994; Perry, 1995; Burnfield, 2004; Mohamed, 2005; Molloy, 2009). However, contrary to previous research, this study found a substantial increase (about 21 to 28%) in ground reaction forces (GRF_{RF}, GRF_{PO}, and PTI) on the foot when walking with shoes as compared to walking barefoot. The most notable methodological difference between this study and recent research is the use of the 0.18 mm-thick F-Scan® in-shoe pressure sensor, while most other recent studies have used the Pedar® system. In the studies using the Pedar, “barefoot” conditions actually involve a 2mm-thick pressure sensor and nylon sock worn between the foot and the ground. It is possible that the current study observed a decrease in GRF_{RF}, GRF_{PO}, and PTI when barefoot because participants were altering their gait to reduce impulse forces due to a lack of cushioning from pressure sensors. This reduction in PTI when barefoot has been observed for runners (Divert, 2005). The 2 mm-thick Pedar insoles may have been sufficiently thick to provide cushioning that eliminated this protective behavior.

Because of the disagreement with previous studies with respect to shoes increasing PTI, some additional testing and analysis was performed to verify the results. While wearing sensors attached in the same manner as in the experiment, three participants took shod and barefoot steps on a force plate. The ratio of the force plate voltage corresponding to the vertical ground reaction force to the measured F-Scan force did not increase when shoes were worn, suggesting that increased shod pressures measured in the study were not an artifact of the F-Scan sensors.

Limitations

This study examined healthy participants from a student population, so these results may not generalize to older adults, or individuals with lower extremity disorders. While the statistical power was adequate for the walking study, it was more limited for the standing studies. The standardized footwear used in this experiment helped to reduce unwanted variability, but it is possible that different shoes or insoles may yield different results.

Conclusion

In this study, floor surface compliance had little effect on plantar pressures when shoes were worn, suggesting that the selection of anti-fatigue mats or carpets would have little effect on plantar pressures. Because shoes mitigate the elevated peak plantar pressures associated with standing and walking when barefoot on hard flooring, these findings suggest that diabetics wear shoes whenever possible to reduce peak pressures that are associated with foot ulceration. The finding that walking with shoes increases ground reaction forces as compared to barefoot walking differs from previous studies, indicating that the underlying mechanisms are unclear.

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CHAPTER VI

Discussion

The overall goal of this research was to understand better the mechanisms by which flooring and footwear affect discomfort during prolonged standing. Although some discomfort mechanisms (e.g., venous pooling and muscle fatigue) have been identified in previous research on standing, physiological measurements associated with these mechanisms were not significantly affected by flooring surfaces (e.g., Cham, 2001; Kim, 1994). Because of this lack of physiological evidence, the mechanisms by which flooring and footwear affect discomfort remain unclear.

The following have been suggested as possible mechanisms for discomfort:

- Muscle fatigue – Fujiwara (2006) showed that when standing, muscles in the leg exhibit sustained contractions to maintain an upright posture. Such sustained, low-level contractions have been shown to be a cause of fatigue (Jorgensen, 1988).
- Venous pooling – During prolonged standing, blood pools in the legs due to gravity and a lack of contraction-relaxation cycles of the leg muscles which assist in pumping blood to the heart (Guyton, 1996). This pooling of blood in the legs causes swelling, which has been associated with discomfort (Kraemer, 2001).
- Plantar Pressure – Although pressures on the bottom surface of the foot during standing average 70 kPa with peaks greater than 140 kPa, sustained pressures of 5 kPa have been shown to cause nerve damage (Rydevik, 1981) and muscle necrosis (Dinsdale, 1974) in animals. The dramatic difference between the low levels of pressure shown to cause injury, and the relatively high levels of pressure on the feet during

standing point to plantar pressure as a possible mechanism for discomfort. However, this topic has received little attention in previous research.

This dissertation focused on investigating plantar pressure as a mechanism that may cause discomfort during prolonged standing. Goonetilleke (1998) has suggested that shifting weight during prolonged standing is a behavior that provides temporary relief from discomfort at the foot resulting from sustained pressure. With significant differences found among flooring surfaces with respect to behavior such as weight-shifting (Chapter 2), plantar pressure was identified as a possible mechanism by which flooring affects discomfort during prolonged standing.

Behavior During Prolonged Standing

Prior to the current research, there was little information describing postures and movements of people that occur during prolonged unconstrained standing. This dissertation used in-shoe pressure measurements to develop variables that describe postural behavior during standing (Chapter 2). These behavioral variables have two promising applications. First, they provide a potential *objective* proxy measurement for discomfort that is more sensitive to differences among different flooring surfaces than traditional *subjective* ratings of discomfort. Behavioral response variables also provide a starting point for identifying discomfort mechanisms.

Weight-shifting and center of pressure (COP) excursion velocity were both positively correlated with discomfort (Chapter 2), suggesting that these behavioral response variables have the potential to be used as objective measurements of discomfort. These variables also have a greater statistical power than subjective discomfort ratings in discriminating among anti-fatigue mats. For example, *post hoc* statistical power calculations showed that only 25% of the participants were required to detect a difference among mats using discomfort ratings were required to detect a difference using COP excursions. However, in order to use behavior as a replacement for subjective discomfort ratings, more research is needed to validate these measures to establish their relationships to mechanisms for discomfort.

This dissertation provides some evidence of a relationship between behavior (i.e., weight-shifting) and mechanisms for discomfort during prolonged standing. In Chapter 2, the behavioral variable of time spent standing primarily on one foot (1FS) was positively correlated with the frequency of weight-shifting. In Chapter 5, standing primarily on one foot was associated with higher peak plantar pressures. It is possible that the higher peak plantar pressures associated with 1FS are a driver for weight-shifting, which would suggest that plantar pressure and weight-shifting are connected.

Mechanisms for Discomfort During Prolonged Standing

Plantar pressure was established as a mechanism for discomfort during standing with the finding that higher pressures resulted in a shorter time to onset of pain (Chapter 4). Pressure causes mechanical deformation of the skin which directly stimulates cutaneous mechanoreceptors. At low pressures, mechanoreceptors responsible for sensing light touch are activated, and pressure is experienced as touch. At higher pressures, nociceptors are activated and this sensation is experienced as pain (Eyzaguirre, 1975).

The changes in touch sensitivity documented in Chapter 3 offer an explanation by which sensations of discomfort may be exacerbated. The same mechanisms causing improved sensation of low-pressure stimuli may also be increasing the perception of discomfort. For example, one possible explanation for the increase in touch sensitivity is that the skin is softening during prolonged standing. As the skin becomes less rigid, a particular pressure would cause greater deformation and could activate more mechanoreceptors sensitive to low pressure (Brand, 1993) as well as mechanoreceptors responsible for discomfort.

Discomfort may be further aggravated by the loading and unloading of the foot due to weight-shifting when standing (Chapter 2). An external pressure can restrict or even stop the flow of blood to soft tissue. When pressure is removed, such as when a foot is unloaded during weight-shifting, blood rushes into the ischemic tissue (Tsuji, 2005). The resulting inflammation causes additional pain and discomfort (Cervero, 2003).

This dissertation was unable to identify specific mechanisms by which flooring affects discomfort during prolonged standing, but provides direction for future research into this topic. The effects of flooring on peak plantar pressure are negligible when shoes are worn (Chapter 5), indicating that pressure can be ruled out as a mechanism by which anti-fatigue mats affect discomfort for shod workers. However, because the benefit of mats for reducing discomfort is well documented in circumstances where shoes are worn (e.g., Redfern, 1995; Cham, 2001; and Chapter 2 of this dissertation), there must be mechanisms other than plantar pressure which affect discomfort.

It is possible that flooring has a practically significant effect on muscle fatigue but that these differences are too small to be of statistical significance with current measurement techniques. Shifts in the mean power frequency (MPF) of electromyograms (EMGs) are commonly used as a measure of muscle fatigue Koumantakis (2001). However, this measurement is subject to considerable variability. Standard deviations are not reported for studies that compared EMG with respect to flooring during prolonged standing (Kim, 1994; Jorgensen 1998; Madeleine, 1998; Cham, 2001). However, even studies that demonstrate relatively low variability have reported average coefficients of variation greater than 0.25 (e.g., Elfving, 1999; Ebenbichler,1998). A small shift in MPF of EMG among flooring surfaces that might correspond to a meaningful change in discomfort may not be detectable due to this variation.

Strengths and Limitations

This dissertation improved upon methods used in previous studies, and further expanded the knowledge of how flooring affects discomfort during prolonged standing. Examples of methodological strengths and improvements include:

- Material properties of 17 commercially available anti-fatigue mats were measured *a priori* and mats were selected for experiments from that population, ensuring that a range of material properties were represented. Previous studies did not systematically select mats.
- In experiments where shoes were worn (Chapters 2, 3, and 5) participants were provided with standardized footwear to reduce unwanted variability. Many previous studies had not provided standardized footwear (e.g., Zhang, 1991; Redfern, 1995; Duarte, 2000; King, 2002; Zander, 2004).
- In Chapter 2, the work task during standing was standardized to reduce variability of behavior and discomfort variables. This is an improvement over many previous studies that did not standardize activity during standing (e.g., Cook, 1992; Kim, 1994; Redfern, 1995; Duarte, 2000; King, 2002; Zander, 2004).
- The distribution of weight between the feet was controlled to reduce variability in pressure measurements when standing (Chapters 4 and 5).

New measurement techniques were introduced that have potential applications in future research. This research was the first to investigate changes in touch sensitivity of the foot resulting from prolonged standing, and developed a protocol for quickly assessing a touch sensitivity threshold using Semmes-Weinstein monofilaments (Chapter 3). This new test method required fewer monofilament applications and can be administered in as little as one-tenth of the time of previous protocols (Dyck, 1993; Berquin, 2010). Because touch sensitivity threshold changes with respect to time, a rapid assessment reduces error by limiting changes in sensitivity that occur while the test is being administered. This method may be useful in other research applications involving temporal changes in touch sensitivity, or in clinical settings where time for assessment may be limited.

Another new measurement technique was the pain pressure threshold at constant pressure (PPT-CP), which tested the relationship between constant levels of pressure and time to onset of discomfort (Chapter 4). This PPT-CP measurement could be used to assist in the design of interfaces (e.g., shoes, seats, backpacks) where sustained pressure is applied to the body. For example, the ratio of the PPT-CP sensitivity (i.e., time to onset of discomfort) to the pressure applied by the product could be used to identify "critical" body locations where the pressure is high in relation to sensitivity. Future research would validate this application of PPT-CP if it can be demonstrated that reducing pressure at these critical locations results in an overall improvement in comfort.

Pressure measurements in Chapters 2, 4, and 5 were taken using the F-Scan system (Tekscan; Boston, MA, USA). The F-Scan has the greatest resolution, greatest sampling frequency, and thinnest sensors of any pressure measurement system currently available (Hsaio, 2002). A thin sensor was very important to ensure that the sensor itself did not provide cushioning which could censor the ability to detect pressure differences among flooring surfaces. However, error in F-Scan measurements has been well documented and the F-Scan has been recommended for comparative measurements rather than for precise measurement of absolute pressure values (e.g., Mueller, 1996; Woodburn, 1996). Because of this, the current research did not depend on absolute accuracy of pressure measurements from F-Scan sensors. In Chapter 2, pressure was evaluated in relative terms to define behavioral variables, using pressure comparisons between feet (i.e., weight-shifting and 1FS) or within the foot (i.e., COP excursions). In all instances where F-Scan measurements were made (Chapters 2, 4, and 5), potential bias was controlled by using randomized, full-factorial experimental designs.

There were several limitations to this research which affected the applicability of some of the conclusions. The participants used in the experiments were young, healthy college students. Results may differ for older participants, individuals with acclimation to prolonged daily standing, and individuals with lower extremity disorders.

Due to a lack of physiological measures linked to discomfort that are sensitive to differences in flooring, this research relied heavily on psychophysical measurements of discomfort. These subjective measurements of discomfort are subject to high variability and limit the ability to discriminate among subtle differences in flooring and footwear.

The low statistical power of pressure measurements for the standing conditions in Chapter 5 was another limitation. *Post hoc* statistical power calculations showed that the experiment had the ability to detect a difference of 13 kPa among surfaces, or about 8% of the overall mean. A major finding of this dissertation is that when shoes were worn, no differences in pressure were detected. This suggests that pressure is not a mechanism by which flooring affects discomfort in shod workers. However, if mats reduce peak pressure compared to a hard surface by less than 13 kPa when shoes are worn, and if a difference of this magnitude does affect discomfort, then it is still possible that flooring affects discomfort by reducing pressure.

This dissertation focused on standing, and many of the findings may not be applicable for activities that require a mixture of standing and walking. For example, mats that are effective during standing (Chapter 2) may not be effective at reducing discomfort during walking, or very soft surfaces that are preferred during standing (Chapter 4) may not be suitable during walking due to potential adverse effects on natural gait patterns (Pinnington, 2005).

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CHAPTER VII

Conclusions

Summary of Major Findings

1. No differences in discomfort were observed among the four tested anti-fatigue mats during prolonged standing. (Chapter 2)

   Although anti-fatigue mats reduced discomfort after four hours of standing as compared to a hard control surface, no differences in discomfort were observed among the tested mats. Because of the large variability in subjective ratings of discomfort, it is possible that discomfort differences among mats exist but were not detected.

2. Behavioral responses to standing were positively correlated with discomfort. (Chapter 2)

   During prolonged standing, both weight-shifting and center of pressure (COP) excursions were correlated with discomfort ratings, indicating that both are observable, objective measures that may be a proxy for discomfort. It has been suggested that weight-shifting is a response to discomfort in the feet, as it allows temporary relief from sustained plantar pressures (Goonetilleke, 1998). Because fatigue of leg muscles has been shown to cause an increase in COP excursions (e.g., Vuillerme, 2002), excursions may provide an indirect measure of leg muscle fatigue.

3. Touch Sensitivity of the plantar foot increases as a result of prolonged standing. (Chapter 3)

   After four hours of standing, sensitivity thresholds on the plantar surface of the foot dropped from 0.56 to 0.36 grams-force (36% decrease) as measured using Semmes-Weinstein monofilaments. Changes in the sensitivity threshold of the dorsal aspect of the foot were not significant, suggesting that plantar pressure during standing may be responsible for changes in touch sensitivity.

4. As the magnitude of plantar pressure increases, pain threshold (i.e., time to onset of pain) decreases. (Chapter 4)

    When a constant pressure was applied to the foot, the onset of pain occurred earlier at higher pressure levels than for lower pressure levels. In pairwise comparisons, each pressure level differed significantly from all other pressure levels, with a decrease in pain threshold (time to onset of pain) as pressure level increased. Higher pressure levels presumably reduced pain threshold by causing greater tissue deformation which in turn resulted in increased activation of mechanoreceptors responsible for the sensation of pain (Eyzaguirre, 1975).

5. Pain threshold is lowest at the midfoot (most sensitive) and greatest at the heel and fifth metatarsal head (least sensitive). (Chapter 4)

    When a constant pressure was applied to different locations of the foot, the onset of pain occurred earliest in the midfoot and latest in the fifth metatarsal head and heel. These differences in sensitivity can likely be explained by the thicker fat pad, and increased callous formation in the heel and metatarsal heads as compared to the midfoot (Klenerman, 1991). Additionally, 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, 1993)

6. During standing, pain originated primarily in regions corresponding to the greatest plantar pressures. (Chapter 4)

    When standing, the origin of pain occurred most often in the heel and first metatarsal head, the regions of the foot associated with the greatest plantar pressures. This result is consistent with finding #4, and suggests that plantar pressure contributes substantially to the development of foot discomfort during standing.

7. Softer floor surfaces reduce peak pressures and load the midfoot when standing barefoot. (Chapters 4 and 5)

   When standing barefoot, more compliant surfaces had increased contact area with the foot, and redistributed pressures from areas of high concentration to the midfoot. This redistribution of pressure resulted in lower peak pressures when standing barefoot on softer floor surfaces as compared to harder floor surfaces.

8. Softer surfaces reduce pain when standing barefoot. (Chapter 4)

   When standing barefoot with one foot on a harder surface, and the other on a softer surface, pain originated in the harder surface in over 75% of trials. This result is likely explained by findings #6 and 7; that peak pressure contributes to the development of discomfort, and that softer surfaces reduce peak pressures by distributing pressure over a larger area.

9. When wearing shoes, floor compliance (softness) had little effect on peak pressures. (Chapter 5)

   Although flooring had a significant effect on peak pressure during barefoot standing and walking, when shoes were worn the effects of flooring on peak pressure were very small or not significant.

Applications

Anti-fatigue mats in the workplace

The findings in Chapter 2 reinforce that mats are effective in reducing discomfort during prolonged standing, providing a strong justification for their use in environments where workers stand for prolonged periods. The reduction in discomfort offered by mats may also be accompanied by a decreased incidence in lower extremity disorders such as plantar fasciitis and hip dysfunction (Werner, 2010). Recent findings on the health hazards of prolonged sitting on the job (e.g., Katzmarzyk, 2009) may also provide a new application for anti-fatigue mats. By creating more comfortable standing conditions, mats could reduce prolonged periods of sitting, and presumably improve comfort and health, for users of sit/stand workstations. Because there is currently no guidance as to what makes a particular mat more comfortable than others during standing, mats can presently be chosen based on other factors such as cost, durability, and safety.

Design of footwear and insoles

In Chapter 4, plantar pressure was identified as a contributing mechanism for discomfort during standing. Flooring appears to have little effect on plantar pressure (Chapter 5), so footwear seems to offer the greatest opportunity for controlling plantar pressure in order to reduce discomfort. This research suggests that when designing footwear, a priority should be reducing peak pressures while limiting pressures at the midfoot. The pain-pressure threshold test at constant pressure (PPT-CP) introduced in Chapter 4 also offers a new method for testing sensitivity to plantar pressure which may be useful for designing of footwear. There are still many unknowns, including the pressure magnitude at which the midfoot may be comfortably loaded, and whether pressures comfortable during standing are also comfortable during walking. However, this research provides designers with some basic guidance for how shoes and insoles may reduce discomfort during standing.

Clinical Applications for Diabetics

Chapter 5 describes that peak plantar pressures are highest on hard surfaces when standing barefoot, but shoes diminish the effects of flooring. This finding has clinical importance for patients such as individuals with diabetes for whom elevated plantar pressures are associated with ulceration (Frykberg, 1998; Sacco, 2009). This research provides evidence that diabetics should wear shoes whenever possible.

Chapter 3 identifies potential bias in the Semmes-Weinstein monofilament test used to screen for protective sensation for diabetics at risk for foot ulceration. More research is needed to quantify the onset and recovery of sensitivity changes, and to verify that these changes occur in individuals with diabetes. The finding of Chapter 3 together with these research extensions may result in a correction in the Semmes-Weinstein test that takes pre-test standing activity of the patient into account.

Standing and Discomfort

The results of this research show that while mats reduce discomfort, the effect of hours spent standing is much greater than the effect of flooring surface. This means that eliminating standing work, using sit/stand stations, or rotating seated and standing tasks will provide greatest comfort to the worker, regardless of flooring surface.

Application of Research Methods

Many of the methods used in this dissertation research may also be useful for evaluating other products that exert sustained pressures on the body. For example, to evaluate the design of a backpack, the PPT-CP test could be used to identify locations on the shoulder that are best suited to withstand sustained pressure. Behavioral measurements such shifting the weight of the backpack across the shoulder may also be useful in evaluating the discomfort associated with a particular design.

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CHAPTER VIII

Recommendations for Future Work

- Discomfort during walking. The conditions for the experiment described in Chapter 2 exclusively involved prolonged standing, but results may have differed for exposure to a mixture of standing and walking. The experiment was likely representative of conditions for workers such as cashiers or surgeons that involve little movement, but including walking in the experimental protocol would help understand the effects of mats on a wider range of working circumstances such as for manufacturing jobs involving work cells or moving assembly lines. It is possible that mats effective during standing are not effective at reducing discomfort during walking.

- Changes in touch sensitivity during standing. Since accuracy of quantitative sensory testing is most critical for screening diabetic patients at risk for peripheral neuropathy, the measurement of the change in touch sensitivity resulting from prolonged standing (Chapter 3) should be expanded to the diabetic population. Additionally, touch sensitivity should be measured more frequently during and after standing to determine the onset and recovery times for sensitivity changes. To identify the causes of change in plantar sensitivity, future studies should measure the skin temperature and moisture of the feet when measuring touch sensitivity. If sustained tissue compression is indeed the primary cause of change in sensitivity, measures of changes in skin stiffness and fat pad thicknesses may also help to identify the underlying mechanics for this sensitivity change.

- Mechanisms for discomfort during prolonged standing. Mats have been shown to reduce discomfort when compared to standing on hard flooring, but plantar pressure does not appear to be a mechanism for differences in discomfort among flooring surfaces (Chapter 5). As a result, other physiological mechanisms should be investigated to explain the improved comfort provided by mats. The finding that COP excursions are lower for softer surfaces suggests that mats may reduce discomfort by providing greater stability, thus reducing muscle requirements to maintain an upright posture. Electromyography of leg and lower back muscles during standing could be used to test the hypothesis that smaller COP excursions are associated with reduced muscle activation. Effective anti-fatigue mats may also allow the body to adopt more comfortable postures, or enable discomfort relieving movements while standing. Using motion capture to measure the position and movement of the ankle, knee, hip, and lumbosacral joint will test the hypothesis that softer flooring enables greater changes in joint angles while standing.

- Plantar pressure distributions at the midfoot. A practical extension of the findings in Chapter 4 that would have implications for the design of footwear would be to determine the limit at which the benefits of reducing peak pressure no longer outweigh the consequences of increased pressure at the midfoot. These findings could be especially important for reducing peak pressure in footwear designed for diabetics, for whom elevated peak pressures have been associated with increased risk of foot ulceration (Frykberg, 1998).

- Occupational costs of discomfort resulting from standing. A practical question on which there is currently little information is whether discomfort during prolonged standing is associated with fatigue or productivity loss in the workplace. In Chapter 2, the effect of discomfort on productivity in simulated work tasks was investigated but results were inconclusive due to issues with learning effects. A cross-sectional field study that examines the effect of discomfort resulting from standing on productivity, worker survivability, and absenteeism could help to justify interventions designed to reduce discomfort such as mats and shoe inserts.

References

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APPENDICES

APPENDIX A

Material Properties of Flooring

This appendix describes the material properties of the flooring surfaces used in this research. Because the surfaces used were generally the main independent variable, providing a precise definition of these flooring surfaces is helpful for interpreting the results. Describing the material properties of the flooring surfaces also makes this research possible for others to replicate.

Introduction to Relevant Material Properties

The material properties measured were chosen for their potential to affect discomfort and pressures on the feet during standing and walking. Some of these properties (i.e., stiffness, work lost, load decay) were established in previous research concerning anti-fatigue mats (Cham, 2001), while some properties (coefficient of friction, durometer hardness) have not been introduced in this context.

Stiffness is a material's resistance to deformation (compression) when an external load is applied (Beer, 2002). A material with a higher stiffness requires more force to compress than a material with lower stiffness. Surfaces with low values of stiffness feel softer than surfaces with high values of stiffness.

Energy Loss represents the amount of energy absorbed by a material when it is loaded (Duggan, 1965). Flooring with low energy loss feels springier than flooring with high energy loss. When a compression load is applied to a material and then removed, some of the energy used to compress the material is not returned when the load is removed. In other words, the force required to compress the material is greater than the force exerted by the mat as it expands back to its original thickness. This occurs because some of the energy is absorbed by the material.

Load Decay is a measure of a material's deformation, or "memory," under a sustained compression load (Cham, 2001). A person standing with feet stationary on a mat with a very large Load Decay would continue to sink into the surface over time, and would leave a footprint when the feet are lifted. Load decay is related to energy loss, but is unique in that it is more dependent on the effects of time.

The *Coefficient of Friction* is a measure of the "slipperiness" between two surfaces. Friction is of interest because it may affect the naturalness of human gait and thus the perceived comfort of a flooring surface. *Durometer Hardness* is a measure of the hardness of the surface of an object, i.e., how resistant it is to surface deformation.

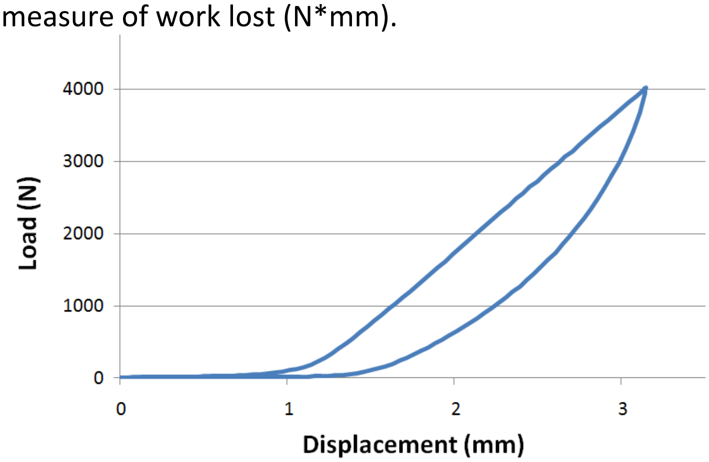
Measurement Methods

Stiffness, work lost, and load decay were measured for each mat using a stationary MTS testing machine (model: Insight 10 SL; MTS Systems Corp; Eden Prarie, MN, USA). See Figure A.1. This device provides precise measurement of how much a mat sample compresses (linear displacement, measured in millimeters) under changing load (force, measured in Newtons).

Figure A.1: MTS material testing machine compressing a mat in a laboratory test

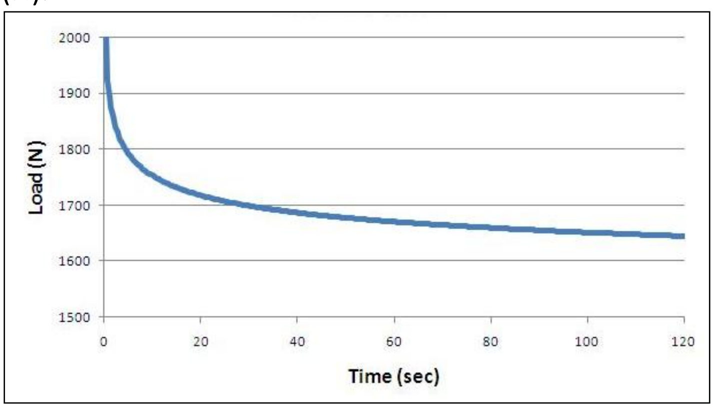
Stiffness and *Work Lost:* Mats were loaded to a force of 4000 Newtons (N) and subsequently unloaded. Three trials were run, each on a different location on the mat. Compression force and displacement were measured and the graph of force vs. displacement was used to determine stiffness and energy lost (see Figure A.2).

Figure A.2: Graph of force vs. displacement as an anti-fatigue mat is compressed and unloaded. The linear portion of the graph is generated as the compression load on the mat is increased. The slope of this line is the measure of the stiffness (N/mm). The curved portion of the graph is generated as the compression load is subsequently decreased. The area between the compression and decompression curves is the measure of work lost (N*mm).



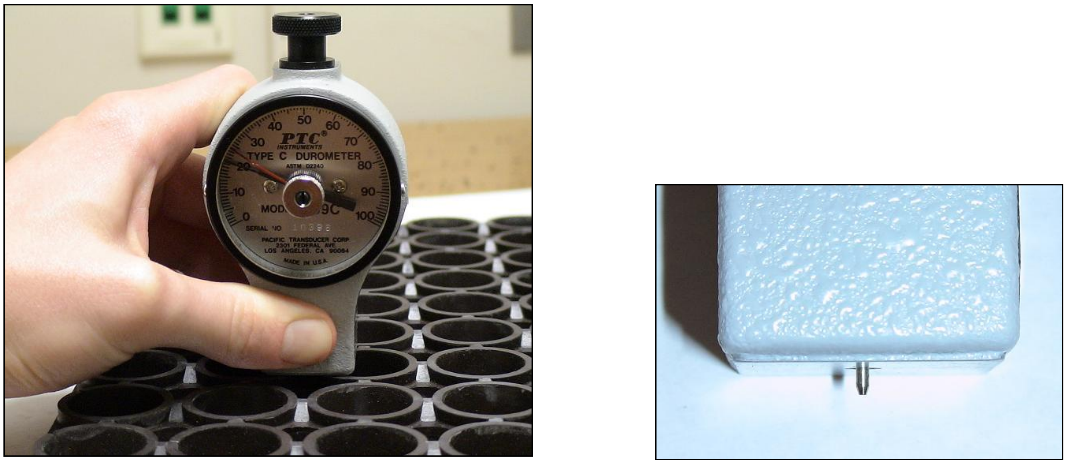
Load Decay: To measure load decay, mats were compressed to a force of 2000 N and the displacement distance associated with the 2000 N compression load was then held constant for two minutes. During these 120 seconds, the machine exerted whatever compression force necessary to maintain the displacement distance. Due to deformation, or memory of the material, this force gradually decreased. The amount that the compression force decreased over time is the Load Decay. Three trials were run, each on a different location on the mat. An example Load Decay curve is shown in Figure A.3.

Figure A.3: Graph of force vs. time as an anti-fatigue mat is compressed to 2000 N and displacement is held constant. The force after 120 seconds is the measure of load decay (N).



Durometer Hardness: This property is measured by pressing a testing device called a durometer (shown below) into the specimen until its flat surface is flush against the object. A small pointed tip on the device exerts force on the specimen, and the hardness measured by device is based on the displacement of the tip. Hardness is similar to stiffness in that it measures a relationship between force and displacement, but differs in that the displacement is superficial and localized to a small area and depth. A PTC® (Los Angeles, CA, USA) type 'C' Durometer, designed for testing rubber and plastic surfaces, was used in this study. Five measurements were made, each at a different location on the material.

Figure A.4: A durometer testing a mat (left) and a close up view of the durometer tip (right)



Coefficient of Friction (COF): The COF is calculated by computing the ratio of the frictional force and normal force (i.e., the force required to slide surfaces across each other and the force pressing the two surfaces together). COF was measured using the static COF testing method described by Chaffin (1992). Two conditions were tested for each surface, to estimate the friction during both barefoot and shod conditions. The COF between the three surfaces and a neoprene rubber surface was measured to estimate the COF when walking with shoes. The COF between the three surfaces and F-Scan® sensor was measured to estimate the COF when walking in the barefoot condition. Five measurements were made for each condition, each at a different location on the surface. The same surface preparation was performed for COF testing as was performed for walking trials, which consisted of wiping the surface with a dust mop.

Results

Table A.1: Material properties for the mats used in Chapter 2 as tested in the laboratory. Values shown are means and (standard deviations). Measurements requiring use of the MTS machine or durometer were not measured for the hard control surface (linoleum tile on concrete). However, on this very hard surface, stiffness, energy lost, and durometer hardness would be very high, while load decay would be very low.

Mat	Load Decay	Work Lost	Stiffness	Durometer	COF: Rubber
A	169 (2)	330 (11.8)	2638 (73)	52 (4.7)	0.48 (0.04)
B	711 (65.9)	527 (17)	942 (68)	22 (1.7)	0.84 (0.02)
C	1639 (217.1)	806 (11.4)	914 (10.4)	38 (0.4)	0.50 (0.03)
D	1988 (57.7)	820 (1.7)	500 (82)	52 (1.3)	0.53 (0.01)

Table A.2: Material properties for all surfaces used in Chapter 5 as tested in the laboratory. Values shown are means and (standard deviations).

Surface	Stiffness	Work Lost	Load Decay	Durometer	COF: Rubber	COF: Sensor
Softer Mat	635 (25.2)	990 (135.4)	417 (7.4)	11 (0.4)	.79 (0.06)	.81 (0.04)
Harder Mat	1864 (29.1)	295 (8.2)	272 (7.6)	44 (0.8)	.66 (0.05)	.69 (0.06)
Linoleum Tile	NA	NA	NA	NA	.35 (0.04)	.59 (0.09)

References

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APPENDIX B

Material Properties of Footwear

This appendix describes the material properties of the athletic shoe used for the experiment in Chapter 5. The shoe used was a model “Gel Kanbarra 5,” manufactured by Asics® (Irvine, CA, USA). The shoe is shown in figure B.1. A major aim of the experiment was to determine how footwear mediates the effects of flooring on plantar pressure, so a detailed description of the material properties of the shoes is important for interpreting the results.

Figure B.1: Gel Kanbarra 5 athletic shoe, manufactured by Asics®

Measurement Methods

The material properties tested were stiffness, work lost, and durometer hardness. These properties are defined in Appendix A.

Stiffness and work lost were calculated by measuring the compression force as the shoe was loaded and subsequently unloaded in an MTS testing machine (model: “Insight 10 SL”; MTS Systems Corp; Eden Prarie, MN, USA). The test protocol consisted of compressing the shoe at a rate of 25 mm/minute to a force of 1000 Newtons (N), then holding displacement constant for 15 seconds before decompressing the shoe at

25 mm/minute. The outer sole of the shoe rested on a flat, 15 cm-diameter aluminum disc, and force was applied to the inner sole by a 45 mm-diameter flat aluminum plunger with a 1.0 mm edge radius. Testing was conducted at the heel and forefoot of the shoe, with three replications for each location. Before a location was tested, five break-in cycles were performed in which the location was loaded to 1000 N and immediately unloaded. Because the results for each location were similar, stiffness and work lost values were averaged across the heel and forefoot locations.

Surface hardness measurements were made for both the outer and inner sole of the shoe using a PTC® (Los Angeles, CA, USA) type 'C' Durometer. Five different locations were tested on both the outer and inner sole.

Results

The measured stiffness for the shoe had a mean (standard deviation) of 80.6 (14.5) N/mm and the work lost was 1849 (214) N*mm. The durometer hardness was 18 (0.7) for the insole and 35 (2.1) for the outer sole.