Applied Ergonomics 46 (2015) 84–90

Contents lists available at ScienceDirect

Applied Ergonomics

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

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

Neal Wiggermann*, W. Monroe Keyserling

Department of Industrial and Operations Engineering, University of Michigan, Ann Arbor, MI, USA

ARTICLE INFO

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

Keywords:
Standing
Pain-pressure threshold
Sensory testing

ABSTRACT

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

1. Introduction

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

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

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

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

* Corresponding author. 1161 Tekulve Rd. #401-20, Batesville, IN 47006, USA.
E-mail address: newiggermann@gmail.com (N. Wiggermann).

http://dx.doi.org/10.1016/j.apergo.2014.07.008
0003-6870/

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

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

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

2. Methods

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

2.1. Participants

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

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

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

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

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

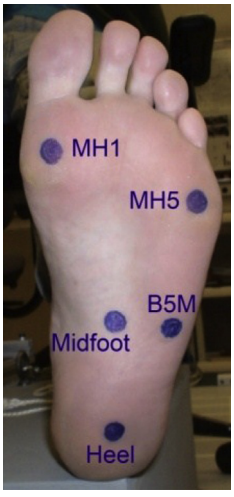

Fig. 2.1. Test locations on the foot for the TPO test.