Journal of Biomechanics 47 (2014) 3767–3770

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

Temperature as a predictive tool for plantar triaxial loading

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ARTICLE INFO

Article history:
Accepted 25 September 2014

Keywords:
Plantar shear
Plantar pressure
Thermography
Diabetes
Ulcer

ABSTRACT

Diabetic foot ulcers are caused by moderate repetitive plantar stresses in the presence of peripheral neuropathy. In severe cases, the development of these foot ulcers can lead to lower extremity amputations. Plantar pressure measurements have been considered a capable predictor of ulceration sites in the past, but some investigations have pointed out inconsistencies when solely relying on this method. The other component of ground reaction forces/stresses, shear, has been understudied due to a lack of adequate equipment. Recent articles reported the potential clinical significance of shear in diabetic ulcer etiology. With the lack of adequate tools, plantar temperature has been used as an alternative method for determining plantar triaxial loading and/or shear. However, this method has not been previously validated. The purpose of this study was to analyze the potential association between exercise-induced plantar temperature increase and plantar stresses. Thirteen healthy individuals walked on a treadmill for 10 minutes at 3.2 km/h. Pre and post-exercise temperature profiles were obtained with a thermal camera. Plantar triaxial stresses were quantified with a custom-built stress plate. A statistically significant correlation was observed between peak shear stress (PSS) and temperature increase ($r=0.78$), but not between peak resultant stress (PRS) and temperature increase ($r=0.46$). Plantar temperature increase could predict the location of PSS and PRS in 23% and 39% of the subjects, respectively. Only a moderate linear relationship was established between triaxial plantar stresses and walking-induced temperature increase. Future research will investigate the value of nonlinear models in predicting plantar loading through foot temperature.

1. Introduction

Diabetic foot ulcers and related lower extremity amputations continue to burden the US healthcare system, with costs estimated to be approximately $30 billion annually (Rogers et al., 2008). With an estimated 100,000 lower extremity amputations each year (Bloomgarden, 2008), the need exists to better understand the pathology of diabetic foot ulcers so improvements to detection and therapeutic practices can be developed. Advancements in the treatment of diabetic foot complications would not only have positive financial implications, but avoiding amputation would also allow the diabetic patient to maintain independence and a greater quality of life.

Conclusive evidence to determine the exact pathology of diabetic ulcers does not currently exist. Previous literature suggests that diabetic patients with significant neuropathy are more likely to develop ulcers because they are unable to perceive minor mechanical trauma caused by moderate plantar stresses to the sole of the foot (Frykberg et al., 1998). The measurement of plantar pressure distribution has been a commonly used technique for assessing the at-risk diabetic foot (Cavanagh et al., 2000). However, additional investigations have challenged the clinical value of plantar pressures in identifying ulcer development. Armstrong et al. (1998) and Lavery et al. (2003) attempted to acquire a threshold value for pressure capable of detecting ulceration, but these investigations were unable to find a highly predictive value. The low sensitivity and specificity values

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http://dx.doi.org/10.1016/j.jbiomech.2014.09.028
0021-9290/

reported by these studies indicate that feet with high pressure values may not ulcerate, while feet with "normal" pressures could ulcerate. A more recent study (Ledoux et al., 2013) enhanced the previous findings by indicating significantly greater peak plantar pressure values for ulcers occurring at the metatarsal heads, which hosted only 25% of the wounds. Additionally, a prospective study by Veves et al. (1992) investigated ulcer development at peak pressure locations but only found matches in 38% of participants.

In addition to plantar pressure, horizontal stresses (i.e., shear) were also postulated to play a major role in the development of diabetic foot ulcers (Dinsdale, 1974). This theory was strengthened by Pollard and Le Quesne (1983), who reported that the locations of maximal shear force have previously predicted ulceration sites in diabetic patients with neuropathy. In addition, Brand (2003) reported that shear forces may induce temperature increases, possibly accelerating the breakdown of tissue and eventually leading to ulceration. The clinical importance of shear was exemplified in more recent studies indicating higher shear stresses in diabetic patients (Yavuz et al., 2008; Yavuz, 2014) as well as differences observed between peak shear and plantar pressure sites (Yavuz et al., 2007). Although the clinical importance of shear has been presented in a few previous investigations, the absence of widely available equipment has hampered research in this area.

Previous investigations have implemented thermographs to analyze loading patterns on the sole of an individual's feet. Brand (2003) measured temperatures under a healthy subject's feet after completing various timed running trials. Changes in temperature profiles, including peak temperature location shift, were seen after running trials were completed (Brand, 2003). Thermographs were similarly used in a study analyzing the effects insoles may have on temperature profiles of the feet (Hall et al., 2004). Hall et al. (2004) reported that six minutes of walking could lead to an approximate temperature increase of 5 °C. Taking these findings into consideration allows for the postulation that increases in plantar temperature are possibly due to mechanical forces acting on the plantar surface.

The purpose of this study was to determine whether statistically significant associations existed between measured plantar stresses and post-exercise foot sole temperature increases quantified with an infrared thermal camera. Significant correlations may suggest that thermographs could be used to assess plantar triaxial and/or shear loading and, therefore, eventually lead to an improved understanding of the biomechanical factors that may induce diabetic foot complications.

2. Methods

Investigators recruited and received informed consent from thirteen healthy volunteers at the Kent State University College of Podiatric Medicine. After completing the admission process, participants were asked to sit down and keep their feet elevated for at least ten minutes so their skin would reach thermal equilibrium (Hall et al., 2004). Pre-exercise baseline plantar temperature profiles were collected using a non-contact infrared thermal camera (Fig. 1a). The infrared camera (TiR2FT, Fluke Corporation, Everett, WA) had a pixel resolution of 160×120 with a thermal sensitivity of 0.07 °C. Temperatures in the range of -20 °C to 100 °C could be measured using the camera.

Participants were asked to walk on a custom-built pressure-shear plate at self-selected speeds on a 3.6-m long walkway. The device was set flush with the walkway and measured $11.4\ \text{cm} \times 14.2\ \text{cm}$. The device consisted of 80 sensors measuring $1.25\ \text{cm} \times 1.25\ \text{cm}$, with a 1.5-mm space between each sensor. The sensors were arranged in an 8×10 array. Additional information regarding the custom-built pressure-shear plate has previously been explained (Yavuz et al., 2008).

Data were collected using the two-step method (Bryant et al., 1999). Subjects were asked to take their first step with their nondominant foot, so the dominant foot lands on the stress plate while walking at self-selected speeds. Participants practiced the two-step method multiple times until necessary adjustments were made to the starting position, so the forefoot would land directly on the stress plate during the second step. Diabetic ulcers tend to occur in the forefoot area, making this region of the foot of primary interest when collecting data (Oyibo et al., 2001; Caselli et al., 2002). After stress data were collected, participants were asked to walk barefoot on a treadmill at 3.2 km/h for 10 minutes. Participants again sat down with their legs elevated so that post-exercise plantar temperatures could be determined with the infrared camera (Fig. 1b). Participants were then asked to walk on the custom-built pressure-shear plate an additional three times to obtain posttest shear stress data (Fig. 1c). Data from at least three trials (1 pre-exercise + 2 post-exercise or 2 pre-exercise + 1 post-exercise) were averaged and used in data analysis. In most cases, we were able to use data from four trials.

Peak values of temperature increase and peak plantar stresses were determined and used for statistical comparisons. Two plantar stress variables were identified and calculated: peak shear stress (PSS) and peak resultant stress (PRS). The PSS was determined by obtaining the maximum magnitude of anteroposterior and mediolateral shear vector additions. The PRS was calculated by vector

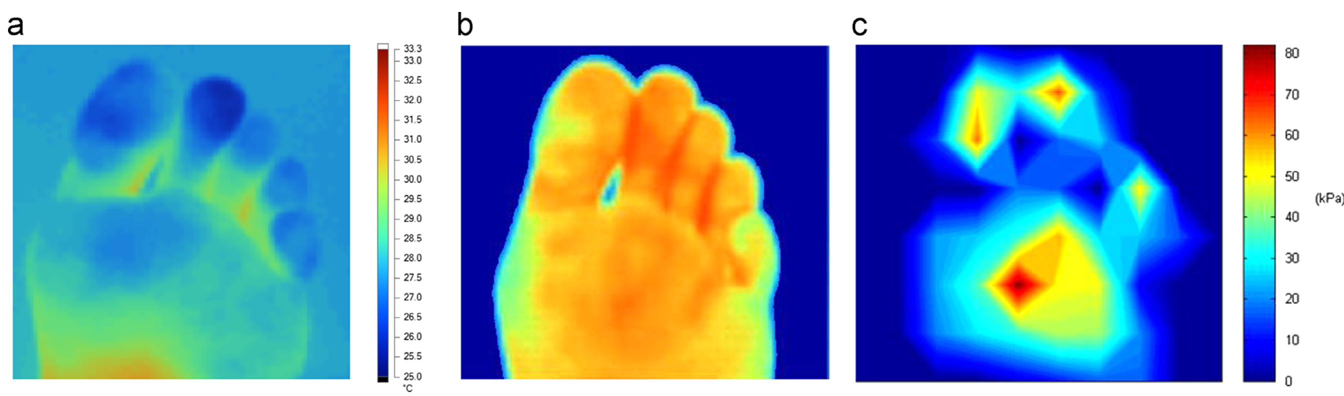

Fig. 1. (a) The depiction of a subject's pre-exercise temperature profile is shown. (b) This is the same subject's post-exercise temperature profile. (c) The peak shear stress (PSS) profile of the same subject is illustrated.