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Effect of gait on formation of thermal environment inside footwear

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ABSTRACT

In this study, the relationship between the gait condition and foot temperature distributions inside footwear was investigated using subject experiments. Mechanical, physical, and physiological variables such as the foot contact force, landing speed, and metabolic heat generation were also measured. Gait motion measurements showed that a large contact force was concentrated in the small area of the heel at the initial contact and later at the forefoot. A faster gait produced a larger contact force, higher landing velocity, higher skin temperature, and larger metabolism during gait. The temperature at the bottom of the foot increased, and the temperature on the upper side decreased. The metabolic heat generation had a basic impact on the temperature profile, and skin temperatures tended to increase gradually. In addition, high-temperature-elevation regions such as the big toe and heel coincided with regions with high-contact loads, which suggested a relationship between the temperature elevation and contact load.

1. Introduction

People normally wear shoes in daily life, and research on footwear is of interest to many people. The foot has an important thermal radiator function for human thermoregulation (Day, 1969). Therefore, when feet are contained within footwear for long periods, the temperature and humidity inside the footwear rise. In one study, the midsole temperature became greater than 50 °C while running during daytime in summer (Kinoshita and Bates, 1996). This can cause discomfort, especially during summer or in hot and humid regions. Skin temperature contributes to the thermal comfort of the entire body and the autonomic thermoregulatory response (Frank et al., 1999). A significant weighting value of 0.07 is used for the foot temperature in a common expression of whole body skin temperature (Hardy and DuBois, 1938), and a whole-body thermal sensation evaluation can be performed using the skin temperature (Takada et al., 2013). The thermal environment such as the temperature inside footwear becomes important in this respect. Moreover, the temperature and humidity elevations inside footwear are recognized not only as a source of discomfort but also as a severe problem that can cause injury or bacterial infection in some cases.

In the context of thermal comfort, many measurements and assessments addressing footwear have been carried out. The foot-skin temperature, air temperature inside footwear, and humidity have commonly been measured, and elevations in these values have been recognized (Kawabata and Tokura, 1993). An in-shoe portable device for plantar pressure, temperature, and humidity measurement was invented (Maluf et al., 2001), and shoe comfort assessments and product evaluations have frequently been conducted (Schols et al., 2004). However, no studies have considered the basics of the heat transfer and temperature distribution inside footwear. Therefore, the authors were interested in the formation of the thermal environment inside footwear.

The heat transfer inside footwear is mainly divided into two mechanisms: (1) expelled heat generated inside the body and (2) heat transfer to/from the footwear surface or through the surface. Thus, a hot feeling may be the result of inner heat generation due to metabolism. In general, heat transfers from a higher to lower temperature region. Therefore, another possibility when feeling uncomfortably warm or hot is that the person's surroundings have a higher temperature than their skin. When considering the conservation of energy, one mechanism that could potentially cause heating inside footwear is the transformation of the mechanical energy of the gait motion into thermal energy. In fact, the maximum contact force at landing was reported to be more than the body weight during running at 3.3 m/s (Chuckpaiwong et al., 2008). This contact force seems to have enough potential energy to heat the inside of footwear. Normally, the walking speed strongly

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affects the peak plantar pressure (Pataky et al., 2008), and this may cause the formation of a different thermal environment in footwear.

The purpose of this study was to identify the influence of the heat generation and transfer changes associated with the gait speed on the formation of the thermal environment inside footwear. A second purpose of the study was to provide a database for walking or even running to be used for thermal comfort optimisation in footwear design.

2. Procedure

Experiments with subjects were conducted to simultaneously evaluate the contact force and skin temperature changes inside footwear. Four gait speeds were selected for the experiment: 3.0, 6.0, 9.0, and 12.0 km/h. The 9.0 and 12.0 km/h gaits were faster than walking. Thus, the gait transitioned from walking to running at 9.0 km/h. In this sense, our gait speeds covered a wide range from walking to running.

The foot-contact force distribution was measured using pressure sensors (Tekscan F-Scan system) at 0.01 s intervals (100 Hz) at a given gait on a treadmill (Ahroni et al., 1998). First, a comparison was made of the force value by a calibration (Hamzah et al., 2008) using piezoelectric force platforms (Kistler model-9287) during simple vertical stepping to ensure the accuracy and timing of the contact force. The time-averaged value was 6.4% lower in the F-scan system. However, the overall output shapes looked similar, and the measurements were repeatable. In fact, some studies have addressed the accuracy of the system, and the present gait condition was similar to that used in previous studies (e.g., Verdejo and Mills, 2004), allowing an analysis of this kind of gait speed. For the purpose of analysing the gait motion, a 9-axis motion sensor (ZMP IMU-Z2) was placed on the very rear surface of the footwear, and measurements were acquired at 0.01 s intervals (100 Hz). The temperatures were recorded (using J thermocouples) at eight different points at 1 min intervals. The measuring points were determined by referring to a previous planter pressure analysis (Burnfield et al., 2004), and included the little toe, big toe, arch, heel, instep, medial malleolus, lateral malleolus, and sublingual to represent the entire foot, as shown in Fig. 1. Since the temperature measurement used several thermocouples simultaneously, the sensors were compared using a calibration bath before the experiment. An exhaled gas analyser (S&Me VO2000) was also used to evaluate the metabolism. Prior to the experiment, an oxygen flow sensor was installed and calibrated, and automatic calibration was performed before every measurement. All of this equipment was synchronized. The body mass was measured before and after the experiment to observe the weight change from sweating. The surrounding weather factors were also measured at 1 min intervals. The global solar radiation, solar radiation reflected from the ground, infrared radiation from the atmosphere and ground (EKO MR-60), air temperature (Pt-100 resistance), wind speed (ultrasonic anemometer), and humidity (capacitance hygrometer) were measured. For reference, the average air temperature, humidity, and wind speed were approximately 28.6 °C (SD 0.2 °C), 72.0% RH (SD 2.0% RH), and calm wind, respectively.

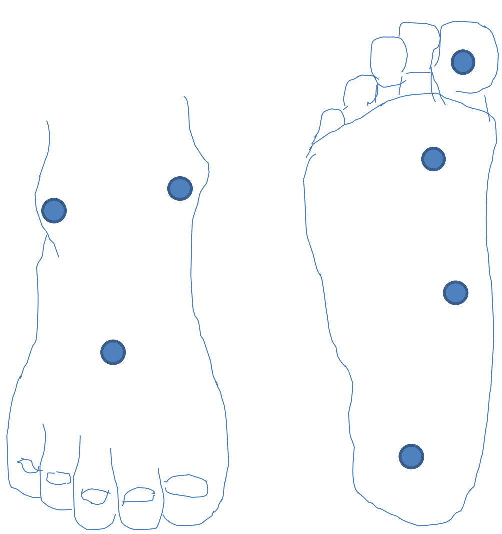

Fig. 1. Temperature measurement points on foot.

All the measurements were taken once a day during a single session, thus preventing the order effect. The participant changed into specified clothing and was weighed to calibrate the pressure measurement prior to the experiment. Sensors were installed 15 min before the measurements began, by which point the participants were acclimated to the initial environmental state in a chamber. The measurements were taken for 50 min in an indoor chamber. After 10 min of rest, a subject performed a gait exercise for 30 min. After this exercise, the subject recovered for 10 min. The subjects wore shoes on their bare feet.

The shoes used in the study were designed as running shoes and had a length of 27.0 cm and a weight of 0.18 kg. The subjects were selected to fit the size. The shoes had a slightly raised heel with a maximum height of 2.0 cm, with rubber cushioning. The upper part of the shoes was made of a porous material.

A total of 17 healthy males, between the ages of 19 and 23, participated in the study. The participants had a mean age of 21.1 years (SD 1.6 year), mean height of 170.3 cm (SD 4.3 cm), and mean weight of 60.1 kg (SD 6.3 kg). All the subjects agreed to be part of the study, and the research was conducted with the approval of the Research Ethics Committee of Okayama Prefectural University.

The data are normally presented as the mean response. In particular, the analysis results for the temperature changes are presented as temperature elevations to remove individual temperature level differences.

3. Results

3.1. Gait motion

An example of the time-dependent gait motion is analysed. The contact force, contact area, and contact force distribution are shown in Figs. 2 and 3. Fig. 2(a) shows the values for a gait of 3.0 km/h and (b) shows them for a gait of 12.0 km/h. In the figures, the contact force is normalized for the body weight. A gait event includes the initial contact, loading response, mid-stance, terminal stance, pre-swing, initial swing, mid-swing, and terminal swing in time order (Uustal and Baerga, 2004). The time is defined as zero at the initial contact. In Fig. 2(a), the contact force and contact area rapidly increase after the heel strike (initial contact). Then, these values increase with time. After approximately 0.50 s, they reach the maximum. Then, the contact force and contact area decrease. After 0.95 s, toe off occurs, and the values become nearly zero again. The time-dependent contact force distributions are also shown in Fig. 3. After the foot contact, when all the force is concentrated on the small area of the heel in Fig. 3(a), the contact force and contact area gradually increase, as seen in Fig. 3(b). Then, the contact force moves from the heel to the forefoot, as seen in Fig. 3(c). Finally, at the time when the heel rises, the contact force is concentrated at the metatarsal and toe neck, and the foot contact terminates. After 1.5 s, another landing occurs, and a new cycle of gait motion starts.