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Evaluation of thermal formation and air ventilation inside footwear during gait: The role of gait and fitting

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ABSTRACT

Comfort is an important concept in footwear design. The microclimate inside footwear contributes to the perception of thermal comfort. To investigate the effect of ventilation on microclimate formation inside footwear, experiments with subjects were conducted at four gait speeds with three different footwear sizes. Skin temperature, metabolism, and body mass were measured at approximately 25 °C and 50% relative humidity, with no solar radiation and a calm wind. The footwear occupancy and ventilation rate were also estimated, with the latter determined using the tracer gas method. The experimental results revealed that foot movement, metabolism, evaporation, radiation, convection, and ventilation were the main factors influencing the energy balance for temperature formation on the surface of the foot. The cooling effect of ventilation on the arch temperature was observed during gait. The significance of the amount of air space and ventilation on the improvement in the thermal comfort of footwear was clarified.

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1. Introduction

Covering the body is a major contributor to the microclimate around the human body, which is the state of temperature formed by the combination of the environment, the human body, and materials. The outer materials influence the heat transfer between humans and their surroundings and the thermoregulation of the human body, thus affecting thermal comfort. Therefore, assessment of coverage thermal insulation has been carried out by several researchers, and a guideline has been provided in ISO9920 (2007), particularly for clothing. Like clothing, footwear serves a physiological function. Although the feet account for only 7% of the body surface area (Hardy and Dubois, 1938), they significantly influence physiological heat exchange. The thermal protection characteristics of footwear play an important role in confining heat inside footwear, particularly in hot environments. Because the feet are dense in sweat glands (Kuno, 1956), high temperatures induce sweating. During exercise, particularly in the heat, which is assumed to be the normal use condition of footwear, there is a larger sweat secretion rate from the dorsal surface than from the sole and plantar side of the toes (Smith et al., 2013). Because sweat production is one of the influential factors in footwear design, evaluation of footwear for moisture disposal has been conducted (Schols et al., 2004; Heus et al., 2005). The subjective perception of the thermal comfort of footwear has been found to be related much more to increased foot temperature than to moisture retention (Arezes et al., 2013). This finding seems to be related to the basic idea that the thermal comfort is related to skin temperature (Bulcao et al., 2000).

In order to provide thermal comfort inside footwear, the temperature and humidity need to be maintained within normal limits. One study reported that the footwear temperature should be kept in the range of 27–33 °C for foot comfort (Kuklane, 2009). Footwear temperatures up to 50 °C have been measured in summer during exercise (Kinoshita and Bates, 1996), and foot temperatures beyond the comfortable range have been measured even for indoor gaits (Shimazaki and Murata, 2015). Cooling the foot may therefore affect the comfort of footwear.

Footwear has multiple functions, including reducing injuries and maintaining hygiene by protecting the foot. One possible solution to cooling feet enclosed in footwear is prompt ventilation. The removal of heat and moisture from inside footwear is achieved mainly by the piston-like action, called bellows action, that occurs during gait (Vokac et al., 1973). Several methods for measuring microclimate ventilation for enclosed spaces have been developed

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(Crockford et al., 1972; Lotens and Havenith, 1988). Havenith et al. (2010) confirmed the validity of a method intended for clothing ventilation after comparing several ventilation methods. Subsequently, Satsumoto et al. (2011) proposed a method that was applicable to footwear. Because the gait motions change depending on the gait speed, the ventilation conditions vary. However, the effects of ventilation on thermal formation inside footwear under various gait conditions are still unclear, and there is no organized data available for use in footwear design.

The thermal aspect of comfort is one of the most important concepts in footwear design. The temperature and air behavior inside footwear contribute to the perception of thermal comfort, and many commercial products have been developed based on the optimization of these parameters. However, there have been no studies on the heat exchanges in footwear that are associated with ventilation of air and thermal comfort. Therefore, this study was conducted to analyze the heat exchanges associated with ventilation and assess their influence on the formation of the thermal environment inside specific footwear. The results of the study also provide a database for designing comfortable footwear with adequate ventilation.

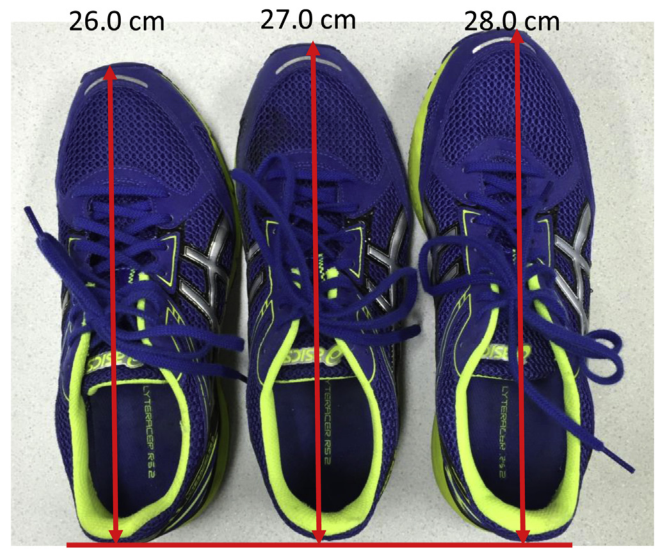

Fig. 1. Footwear used in the experiments.

2. Methods and materials

Experimental measurements were performed in this study to examine the relationships between the characteristics of footwear, the microclimate inside footwear, ventilation, and gait. First, the characteristics of the footwear were determined, namely, their fitting and air ventilation rate. Then, to analyze the microclimate conditions inside the footwear, the inside temperatures were measured during gait. The ambient weather conditions were also measured, including the global solar radiation (with an EKO MR-60), the solar radiation reflected from the ground (with an EKO MR-60), the infrared radiation from the atmosphere and ground (with an EKO MR-60), the air temperature (with a thermistor), the wind speed (with a Kanomax model 6531), and the humidity (with a polymer resistance hygrometer).

Most studies of the thermal comfort of footwear have been conducted using foot manikins. However, the characterization of footwear under real gait is essential and requires human participants. All of the measurements used in this study were obtained during a single session. The participants were seven healthy adult males (1.72 ± 0.07 m height, 61.8 ± 4.7 kg weight, and 23.8 ± 4.3 years old). After informed consent was obtained from all the participants, the subject experiments were conducted with the approval of the Research Ethics Committee of Okayama Prefectural University.

2.1. Condition settings

Four gait speeds, transitioning from walking to running, were selected for the experiments: 0.0, 3.0, 6.0, and 9.0 km/h.

The participants changed into specified clothing and were acclimated to the initial environmental state in a chamber before the experiment. They wore shoes on their bare feet to eliminate any effect from socks.

2.2. Footwear characteristics

For the purpose of eliminating the influence of different types of footwear on the microclimate inside the footwear, we studied different sizes (26.0, 27.0, and 28.0 cm) of specific footwear designed for running to analyze their fitting (Fig. 1). The footwear had a slightly raised heel with rubber cushioning and a maximum height of 2.0 cm, and the outsides of the shoes were made of porous material. When considering the airflow inside footwear, the gap space between the foot and the footwear is important. There are several techniques for modeling the foot and footwear shapes (e.g., Kouchi, 1995; Mauch et al., 2009), but a simple method was used in this study. In order to assess the overall fitting between the foot and the footwear, occupancy was used as an indicator of the gap space volume. The occupancy R [no units] is the ratio of the volume of the foot to the volume of the interior of the footwear and is expressed as follows:

$$R = \frac{V_{foot}}{V_{footwear}} \tag{1}$$

where V denotes volume [m^3]. The volume of the foot V_{foot} was measured by the water displacement method using Archimedes' principle (Manna et al., 2001). After marking the upper limit of the footwear on the foot with the footwear on, the participant's foot was positioned in a water bath filled with water to ensure that the mark met the water surface, and the volume of spilled water was taken as the volume of the foot. The volume of the footwear $V_{footwear}$ was measured using a fine powder. The footwear was filled with the powder, and then the mass of the powder was measured. The volume of the footwear was obtained by dividing the mass of the powder by its density (1.09 kg/m^3). The powder was put inside a plastic bag so that it could deform smoothly and freely. The volumes were determined from the masses of the spilled water and powder, using an electrical balance with a 0.1-g resolution (Shimadzu ELB3000).

2.3. Ventilation rate measurement

The tracer gas method was used for ventilation rate measurements (Havenith et al., 2010; Ke et al., 2014), as shown in the schematic diagram in Fig. 2. The tracer gas, CO_2, was mixed with air and injected at four locations inside the footwear (upper, bottom, inner, and outer sides) using a perforated tubing system. After the inlet flow into the footwear was enriched with CO_2, the flow circulated through the system via the connected pump. The flow rate was measured at 1-s intervals (Azbil MQV), and the tracer gas concentrations were measured at the inlet and outlet, and in the ambient environment (Vaisala GMP343). The ventilation rate *Vent* [L/min] was calculated using the following expression:

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