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RESEARCH ARTICLE

THERMAL EQUATIONS FOR PREDICTING FOOT SKIN TEMPERATURE

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ABSTRACT

PURPOSE:

Studying the foot skin temperature of both the young and elderly is important for preventing foot diseases and improving thermal comfort and variability during gait. However, few studies have predicted the thermal conditions in footwear under different variables. The aim of this study is to therefore formulate thermal equations for both the young and elderly to predict their foot skin temperature under the variables of age, gender, activity level and various properties of different types of footwear.

METHODOLOGY:

A total of 80 participants between 20 and 85 years old are recruited in this study, including 40 younger subjects (mean: 23.0; SD: 4.05) and 40 elderly subjects (mean: 69.8; SD: 4.59). They are tasked to sit, walk and run in a conditioning chamber.

FINDINGS:

Regression equations for predicting the foot skin temperature of the young and elderly people are formulated, with R squares of 0.513 and 0.350 respectively. The level of activity is the most important factor when predicting the foot skin temperature. The material properties of the footwear also show a significant impact on the foot skin temperature of the elderly.

Value: The findings of this study provide the basis for better thermal comfort and help to facilitate the footwear design process.

KEYWORDS

foot temperature, physiological factors, footwear, activities, prediction equations

INTRODUCTION

The feet have the physiological function of a heat exchanger, thereby acting as a thermal radiator for the thermoregulation of the human body when they come into direct contact with the external environment. According to previous studies, a comfortable foot temperature ranges from 20°C to 33°C, while feelings of discomfort range from 35°C to 38°C [1]. When the foot is subjected to high temperatures inside footwear, higher humidity which promotes the growth of microorganisms (e.g. fungi and bacteria), and eventually result in chronic foot diseases and a greater risk of foot ulcers [2,3]. However, lower foot temperatures would result in a reduction of foot sensation and afferent information, such as temporary sensory loss, and lead to an increase in gait variability, changes in joint movement and reduced electromyography activity of the muscles of the lower limbs [4,5]. Most studies on footwear interventions have examined how they control balance, gait and kinematics, such as the positioning of the foot, reducing shocks for stability, redistributing the plantar pressure, etc. However, recent evidence supports that the in-shoe temperature is also a critical factor that not only enhances the overall wear comfort of footwear, but also protects the feet against different external environments and conditions of use. The in-shoe temperature could be influenced by various factors, including physiological factors (e.g. gender and age), work/activity intensity, footwear construction and materials as well as the shoe microclimate [1]. During daily life, heat is generated and accumulated in footwear due to blood flow, muscle contractions, frictional forces and viscoelastic heating, which are counteracted by the processes of heat loss, such as radiation, conduction and evaporation. The heat loss takes place through blood flow, from the skin and through other mediums, like footwear with low insulation [6]. However, previous studies have mainly focused on studying the temperature changes on different locations on the feet, as well as temperature changes due to age and gender differences, gait speed and protective footwear. The aim of this study is to therefore integrate the key parameters that affect the thermal environment inside the footwear and formulate numerical equations for the factors of age, gender, activity level and material properties of different footwear to predict the foot skin temperature changes in various types of footwear. It is anticipated that the findings of this study would act as a reference source for the design and development of footwear with better wear comfort.

EXPERIMENTAL

PARTICIPANTS

A total of 80 participants are recruited in this study. Forty (40) are younger between 20 and 39 years old with 24 women and 16 men (mean: 23.0; SD: 4.05). The other 40 participants are elderly people who are between 65 and 82 years old with 25 women and 15 men (mean: 69.8; SD: 4.59). The inclusion criteria are individuals who have no serious foot problems, are free from prescription medication, have no history of cardiovascular disease, and able to walk independently for a long period of time. The body mass index (BMI) of the younger participants ranges from 15.0 to 27.1 kg/m^2 (mean: 21.2; SD: 3.0), while the BMI of the elderly subjects ranges from 17.51 to 29.04 kg/m^2 (mean: 22.87; SD: 2.98). Their foot size ranges from a European size 36 to 44 (mean size 38) for the women and 37 to 45 (mean size 41) for the men. Written informed consent was provided by all of the participants before they took part in the study.

EXPERIMENTAL PROTOCOL

The experiment was carried out in a conditioning chamber in ambient conditions with a controlled temperature of 22±1°C, humidity of 60±5% and air velocity of 0.24±0.01 m/s [7]. All of the participants were required to wear two types of sports shoes, which have a similar shape and design. However, the upper of the shoes is made of different materials, in which one is made of leather and the other of mesh spacer fabric (see Figure 1). Their properties with the specific testing standards are shown in Table 1. The participants also had to wear a standard sports outfit made of cotton with a clothing insulation equal to 0.3 clo, which consisted of a pair of trousers and a long-sleeve T-shirt. The younger participants were to take part in three activities for each type of footwear, including sitting, walking and running, while the elderly participants were only required to sit and walk for each type of footwear. Prior to the commencement of the wear trial, the participants were requested to sit in the conditioning chamber for 30 mins for acclimatization purposes. The length of the sitting task was 20 mins while the walking and running tasks were 30 mins each and took place on a treadmill at a speed of 3 km/hr and 7 km/hr respectively. To reduce possible order effects, the sequence of the tasks was randomized for each subject. An infrared imaging camera (FLIR T420bx, FLIR® Systems, Inc.) with a thermal sensitivity of <0.045°C was used to record the skin temperature of the foot on two occasions: (1) before each test took place, and (2) immediately after the testing from the plantar view, at a distance of 0.8 m. The camera was kept perpendicular to the foot area of interest during recording [8].

FIGURE 1: FOOTWEAR: LEATHER SPORTS SHOES (LEFT) AND MESH SPORTS SHOES (RIGHT)

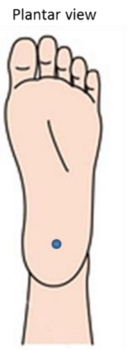
TABLE 1: PROPERTIES OF FOOTWEAR

	LEATHER SHOES	MESH SHOES
TYPE OF FABRIC	SYNTHETIC LEATHER	MESH SPACER FABRIC
Thickness (mm)	4.74	1.90
Thermal conductivity (with KES-F7 Thermolabo) (W/cm·K)	0.040	0.042
Thermal insulation (with KES-F7 Thermolabo) heat retention (%)	53.69	42.99
Air resistance (with KES F8 air permeability tester) (kPa·s/m)	N/A	0.01
Water vapour transmission rate ASTM E96 (g/m^2·hr)	0.84	38.06
Covered area - Female (cm^2)	498.84	494.26
Covered area - Male (cm^2)	505.24	505.64
Surface Area- Female (cm^2)	805.91	758.27
Surface Area- Male (cm^2)	914.42	838.13

STATISTICAL ANALYSIS

Only the thermal images of the right foot were processed by using Matlab R2008a. The temperature point on the plantar of the heel (centre) was extracted for analysis (see Figure 2). Multiple linear regressions (stepwise method) were conducted by using the Statistical Package for the Social Sciences (SPSS) Version 19.0 (SPSS Inc., Chicago, IL) to examine the impact of gender, footwear and their properties, and types of activities on the foot skin temperature to formulate two thermal equations that would predict the foot skin temperature of both the younger and elderly participants respectively. Pearson's correlation coefficients were also used to evaluate the relationships among these factors. The significant level of the statistical analysis was set at 0.05.

FIGURE 2: TEMPERATURE POINT ON PLANTAR OF HEEL (CENTRE) EXTRACTED



RESULTS AND DISCUSSION

MATERIAL PROPERTIES OF FOOTWEAR

Table 1 shows the properties of the two types of sports shoes which have a similar performance in thermal conductivity. However, the shoe fabricated from mesh spacer fabric is much thinner and has lower thermal insulation properties (lower percentage of heat retention) than the shoe fabricated with leather fabric. As the mesh sports shoes contain openings, they have a much higher air permeability and water transmission rate in comparison to the leather sports shoes. However, the leather sports shoes have a greater covered area and surface area than the mesh sports shoes, except for the covered area of the two sports shoes for the male subjects. It is anticipated that heat and water vapour would be more easily transferred and dissipated from the mesh sports shoes as compared to the leather sports shoes as more of the feet are exposed to the environment.

EQUATIONS FOR PREDICTING FOOT SKIN TEMPERATURE

The foot temperature (heel) is significant between the younger and the elderly subjects (P=0.000) with no significant difference was found between the two genders (P=0.280). Therefore, two thermal equations for predicting the foot skin temperature were formulated for the younger and elderly subjects respectively based on various factors, including the material properties of the footwear, physiological factors of the foot and level of activity. For the younger subjects, only the level of activity was found to be significantly correlated to the measured temperature point on the planar of the heel, in which the Pearson's correlation coefficients among foot temperature and sitting, foot temperature and walking, and foot temperature and running are 0.359, -0.717 and 0.359 respectively. The equation for the younger subjects with an R square of 0.513 is shown below:

$$T_y = 35.001 - 3.623W$$

where

- T_y: Foot temperature at planar of heel of younger subjects (°C), and
- W: Walking activity.

For the elderly people, the foot skin temperature at the planar of the heel is significantly correlated to all of the properties of the footwear, activity level and footwear type, in which the Pearson's correlation coefficient between the foot temperature and walking is the highest (0.575). The equation for the elderly participants with an R square of 0.350 is shown as below:

$$T_e = 29.593 + 2.488W – 0.016V$$

where

- T_e: Foot temperature at the planar of heel of elderly subjects (°C);
- W: Walking activity; and
- V: Water Vapour Permeability.

According to the thermal prediction equations for both groups of individuals, activity level is the most important factor when predicting the temperature of the foot during their daily life activities. This result makes sense since more heat would be generated from the body during dynamic activities. Previous studies have found that the plantar foot temperature increases during walking in both young and older adults, in which the foot temperature increases by around 5°C with walking [6,9]. In the summer, the temperature in the midsole area could be more than 50°C while running during the day [10]. Only the water vapor permeability of the footwear was included when forming the thermal equation for the elderly. This is due to the physiological differences between the young and elderly subjects, and the elderly are more sensitive to the footwear materials in comparison to their younger counterparts.

The temperature point at the planar heel was chosen to form the prediction equation because the temperature on the plantar of the foot, especially the heel area, is clearly increased during gait. This is because the heel is in contact with the ground mostly during gait, the sliding friction between the foot and the sole of the shoe, and the environmental variables, such as air temperature and solar radiation, would take place and result in higher temperatures in a shoed foot. Increases in the gait speed mean greater contact force and higher landing velocity, and the therefore, higher foot temperature [11]. Although the R square for the two thermal equations formed is moderate, it is still useful for manufacturers to predict the in-shoe temperature of both younger and older consumers when designing footwear for them, which could facilitate the development and production processes. In the future, more temperature points on the foot could be included in the regression model so as to increase the R square of the heat equations. Validation would be also required for the equations in order to increase reliability.

CONCLUSION

In this study, thermal equations for predicting the foot skin temperature of young and elderly subjects have been established respectively, whilst significant foot temperature differences are observed between the two age groups. Level of activity has proven to be the most important factor when forming the equations, while the water vapor permeability of footwear is only included in the thermal equation for the elderly. The findings of this study provide the basis for designing common footwear for different age groups.

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