A DEVICE FOR ESTIMATING THE FOOTWEAR QUALITY AND PHYSIOLOGICAL SIMULATION OF THE HUMAN FOOT

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Abstract

A sweating thermal foot manikin was developed for evaluating the thermal and evaporative resistance of footwear. The sweating thermal foot manikin can be programmed to simulate physiological patterns of conductive, convective and evaporative heat loss. Using algorithms developed in parallel human studies, the manikin can simulate the initiation and magnitude of non-evaporative and evaporative heat loss based on core and skin temperatures. The system comprises a computer controlled system for regulating the heaters in each of the 16 segments of the foot, as well as the sweating function provided by peristaltic pumps. Each of the 16 segments is autonomous; its heating and sweating responses are controlled independently, thus the calculation of the heat exchange can also be determined for each segment separately. Segments are composed of one temperature sensor, which measure the segment skin temperature, heaters for the segment temperature control and artificial sweating glands, which simulate the human sweating. The segment thermal and evaporative resistance values are calculated from the segments temperature sensors data, segments control algorithm calculated power data and the ambient temperature sensor data. With segments we can find which part of the footwear are worse qualities, what is the base information for the manufacturer and user. Results of the footwear evaluation were compared with the results obtained for identical footwear with other foot manikins. Foot manikin characteristic studies with an infra-red camera show some construction and control drawbacks, which we will tray to improve.

Keywords: Thermal foot manikin, Evaluation of footwear, Physiological simulation, Evaporative resistance, Thermal resistance.

Presenting Author's biography

Mitja Babič was born in 1981 in Koper, Slovenia. He attended Faculty of Electrical Engineering, University of Ljubljana, Slovenia, where he obtained the B.Sc. degree in Electrical Engineering in 2005. He is currently a junior researcher at the department of Automation, Biocybernetics and Robotics, at the "Jožef Stefan" Institute of Ljubljana, Slovenia. His research interests include humanoid robotic shoulder complex and parallel robots.

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1 Introduction

Selection of proper protective clothing and footwear in extreme conditions is very important and requires biophysical evaluation (Fourt in Hollies, 1970; Hollies in Goldman, 1977; Newburgh, 1968). Inappropriate footwear is the main cause for freezing and non-freezing cold injury of the feet. Ensuring that footwear meets minimal biophysical standards is therefore essential in preventing cold injury. The aim of the presented work is biophysical evaluation of footwear for different climates (Santee et al., 1994). In this paper we present a device for the evaluation of thermal and evaporative resistance of footwear.

2 Calculation of thermal resistance

To estimate and compare different footwear we need some type of comfort measuring tool, which include mechanical and ergonomic comfort. The primary measurement tools for estimating thermal footwear comfort are thermal resistance and permeability of water vapor, or sweat evaporation.

2.1 Physical background

We can take a body in a shape of cylinder with length L and constant intersection A. We have on the one part of the cylinder a constant heat flux (P), with a constant temperature T_1, (ex. 35 °C), and on the other side we convey away the heat flux (cooling the stick) so this side have a constant temperature T_2 (ex. 15°C). On the side the cylinder is insulated (Fig. 1 a).

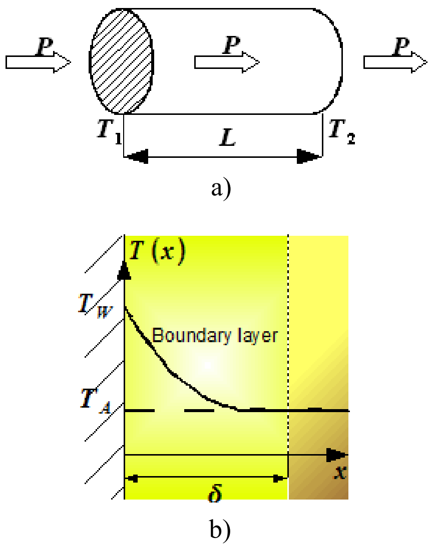

Fig. 1 Heat conduction (see text for details)

Heat flux P is directly proportional to the difference of temperature $T_1 - T_2$ and to intersection A (through which the heat flow), and inverse proportional to the length L (on which there is the temperature difference). Dependence of different materials is carried out with the parameter λ (material thermal conductivity), which give

$$P = \lambda A(T_1 - T_2)/L . \quad (1)$$

How quickly substances transmits warmth depends on thermal conductivity λ (measure unit W/mK). Good temperature conductors (e.g. metals) have thermal conductivity values around hundred or more of W/mK. Substances which have small values of thermal conductivity (around hundredth or tenth of W/mK) are heat insulators, e.g. air, mineral wool, etc. The best thermal insulator is calm air (λ around 0,025 W/mK). Wool is a good thermal insulator because it keeps air inside its fibers.

Similarly we can express the transfer of heat flux from wall to air. The wall has usually for some degree different temperature as the vicinity air. The transition of temperature from air temperature T_A to wall temperature T_W is carried out in a thin (around a cm thick) stratum of air near the wall, which is called boundary layer (Fig. 1 b); the thickness of the boundary layer is δ.

Density of heat flux from wall to air (or in the inverse direction, if air is more warm that the wall) is directly proportional to the difference of wall and air temperature, as

$$P / A = \alpha(T_W - T_A) \quad (2)$$

The proportional factor α (dimension W/m^{2}K) is called conversion ratio; which depends on thermodynamics characteristic of wall and air, and on viscosity and speed of air near the wall. Wind that blow near the wall take heat away from the wall, which cause bigger α at bigger wind speed (in this factor is included also the convection of air over the wall).

If we express the formula (2) in the form of $(P = AT/R)$, we can find out that 1 m^2 of boundary layer have thermal resistance $1/\alpha$ (= thermal resistance of the boundary air layer for 1 m^2 of wall).

Usually we are more interested on temperature of air instead of temperature of wall (e.g. T_I is the wall inner side temperature and T_O is the outer side temperature of wall). We can express the law of temperature conductivity with the difference of inner and outer air temperature, so we are considering the resistance of the wall and resistance of air at both parts of wall

$$P = A(T_I - T_O)/R . \quad (3)$$

So we have found the measure for estimating the footwear quality, thermal resistance

$$R = A(T_I - T_O)/P . \quad (4)$$

In the following section the basic equations for calculating the thermal resistance of each segment of manikin and the total resistance of manikin will be carried out.

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2.2 Thermal resistance

Thermal resistance for each manikin segments can be expressed as

$$R_{T,i} = \frac{(T_{S,i} - T_A) \cdot A_i}{H_{T,i}} \quad , \tag{5}$$

where $R_{T,i}$ is the segment i thermal resistance, $T_{S,i}$ is the segment i skin temperature, T_A is the ambient (air) temperature, A_i is the area of segment i and $H_{T,i}$ is the given power to segment i (loss).

We can compound the total thermal resistance as the sum of all segments resistances

$$R_T = A\left(\sum_i \frac{A_i}{R_{T,i}}\right), \tag{6}$$

where A is the total area of the manikin and A_i is the area of segment i.

When we estimate thermal resistance, the air temperature is lower than skin temperature ($T_A < T_{S,i}, \quad \forall i = 1,...,16$). Normally we keep temperature gradient around 20 °C.

2.3 Estimation of evaporative resistance in isothermal conditions

The evaporative resistance for each manikin segments can be expressed as

$$R_{E,i} = \frac{(p_i - p_A) \cdot A_i}{H_{E,i}} \quad , \tag{7}$$

where $R_{E,i}$ is the evaporative isothermal resistance of segment i, p_i is the partial water vapor pressure of segment i (in saturation), p_A is the ambient (air) partial vapor pressure , A_i is the area of segment i and $H_{E,i}$ is the given power to segment i (loss).

We can compound the total evaporative resistance as the sum of all segments resistances

$$R_E = A\left(\sum_i \frac{A_i}{R_{E,i}}\right), \tag{8}$$

where A is the total area of the manikin and A_i is the area of segment i.

The partial saturation vapor pressure at temperature T is calculated from the empirical relation

$$p_{sat}(T) = 133.3 \cdot \exp\left(18.6686 - \frac{4030.183}{T + 235}\right). \tag{9}$$

For ambient (air) partial vapor pressure we can write

$$p_A = p_{sat}(T_A) \cdot (RH_A / 100) , \tag{10}$$

where RH_A is the relative humidity of air. We suppose for each segment relative humidity to be $RH_i = 100\%$, so the partial water vapor pressure for segment i is

$$p_i = p_{sat}(T_i) \, . \tag{11}$$

For evaluation of evaporative resistance in isothermal conditions we must assure, that temperature of air is equal to skin temperature ($T_A = T_{S,i}, \quad \forall i = 1,...,16$). Under these circumstances the heat transmission is dependent only on evaporation. It means that the segment given heat power $H_{E,i}$ is equal to the process cooling evaporative power on skin.

2.4 Estimation of evaporative resistance in nonisothermal conditions

Evaporative resistance for each segment of the manikin on nonisothermal conditions can be expressed as

$$R_{S,i} = \frac{(p_i - p_A) \cdot A_i}{(H_{S,i} - H_{T,i})} = \frac{(p_i - p_A) \cdot A_i}{(H_{S,i} - \frac{(T_{S,i} - T_A) \cdot A_i}{R_{T,i}})} \quad , \tag{12}$$

where $R_{S,i}$ is the evaporative non isothermal resistance of segment i, p_i is the partial water vapor pressure of segment i (in saturation), p_A is the ambient (air) partial vapor pressure , A_i is the area of segment i, , $T_{S,i}$ is the segment i skin temperature, T_A is the ambient (air) temperature, $R_{T,i}$ is the thermal resistance of segment i (previously measured) and $H_{S,i}$ is the given power to segment i (loss).

We can compose the total evaporative thermal resistance as the sum of all segments

$$R_S = A\left(\sum_i \frac{A_i}{R_{S,i}}\right), \tag{13}$$

where A is the total area of the manikin and A_i is the area of segment i.

When we estimate evaporative resistance in nonisothermal conditions, the air temperature is lower than skin temperature ($T_A < T_{S,i}, \quad \forall i = 1,...,16$). Normally we keep temperature gradient around 20 °C.

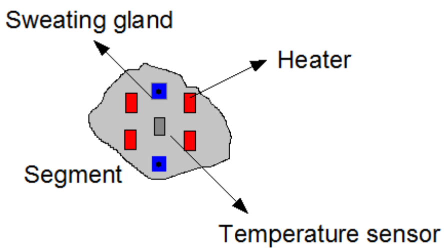
3 System description

Fig. 2 shows the foot manikin system. The system is composed of a personal computer, electrical control system, sweating system and the thermal foot manikin. Hereafter we will shortly describe each part.

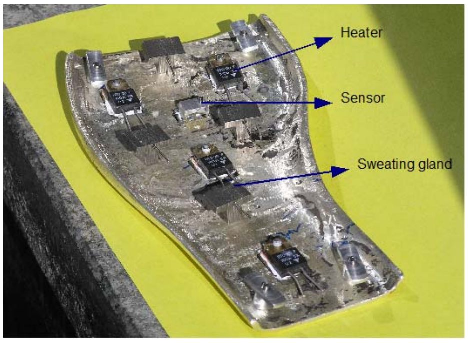
Fig. 2 Foot manikin system

3.1 Foot manikin

The foot manikin is composed of 16 segments. Segments are made of the alloy of silver and copper (approximately 95%:5%), because silver has high thermal conductance, which causes optimized heat flux from heaters to the measured material, whose resistance is measured. Also silver segments tend to have a homogeneous temperature distribution on the whole segment. Each segment has one temperature sensor, which measure the segment skin temperature $T_{S,i}$, heaters for the segment temperature control and artificial sweating glands, which simulate the human sweating. The segment model is shown in Fig. 3 a).



a)



b)

Fig. 3 a) Segment model b) The model of the foot sole

The measurement and control process treats each segment as an autonomous part. Based on the temperature sensor data, the control algorithm controls the heaters in order to reach the desired segment temperature. We can also control the sweating system, which wets sweating glands appropriately. Segment thermal resistance calculation is based on the data obtained from temperature sensor $(T_{S,i})$, the ambient (air) sensor (T_A) and the control algorithm calculated power (P_i), given to the heaters.

The model part of the foot sole is shown in Fig. 3 b). With the appropriate distribution of heaters and sweating glands we try to reach a homogeneous sweating and heating of the whole segment.

3.2 Control system

The control system can be divided into three parts: the software part, the electronics part and the sweating system.

3.3 Sweating system

The sweating system is made of two peristaltic pumps, artificial sweating glands and conveyance tubes. Pumps are controlled by the computer via serial communication. We can control the pumps speed to influence the flow of water through the sweating glands, what simulates the intensity of foot sweating. The software allows starting, stopping and changing the speed of the pumps. An algorithm which simulates the foot sweating depending on the foot skin temperature is integrated in the software (Taylor et al., 2006), as $v_p = f(T_{S,i},...,T_{S,n})$, where $v_{p,j}$ is the pump j speed (j=1,2) and $T_{S,i}$ is the segment i skin temperature (n is the number of segments, 16).

3.4 Electrical control system

The electrical control system consists of the power supply, National Instruments (referred as NI) PXI platform and the power output.

The base of the system is the NI PXI platform and the NI PXI control unit, which are functioning in the Microsoft Windows XP environment. The PXI platform contains the following card.

The connection between the personal computer and the NI PXI platform is made of the NI CardBus 8310 card, which together with the CardBus-to-PCI bridge, provides a transparent link where all PXI modules appear as if they are PCI boards within the computer itself. It allows an easy communication with the selected PXI module.

Two NI 4351 cards acquire data from temperature sensors. The properties of the card are high accuracy, resolution and big factor CMRR - common mode rejection ratio. This is achieved with the help of 24-bit sigma-delta analog-to-digital converters with differential analog inputs. The primary function of the card is to measure temperature with thermocouples or resistance temperature detectors, but the card can also measure DC voltage. For accurate measurement the cards have two current sources, which supply 25 μA for measurements with thermocouples, and 1 mA for measurements with resistance temperature detectors.

The foot manikin has 16 Pt 1000 resistance temperature detectors, which are supplied with current source of 1 mA. The length of the connection cables form the foot manikin to the controller is more then 3 m, so we need to reduce the influence of the wires resistance to the measurement process in order to increase the measurement accuracy. For that reason a three wire connection is used to connect the temperature detectors (Fig. 4). In this configuration only wire resistance R_{L1} adds error to the measurement.

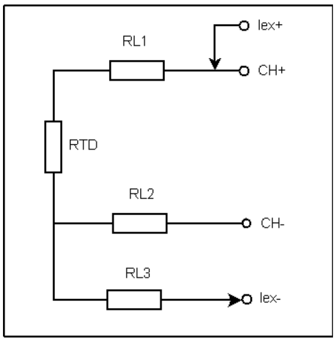


Fig. 4 Temperature measurement

The NI 6221 card has digital inputs and outputs. With this card we control opto couplers, which turn the heaters on and off. For heating segments we use power resistors RTO 20, which principal property is that power-temperature characteristic negligible change with temperature change.

The last NI PXI card is a serial communication card. This card has four serial RS 232 ports which are used to control the pumps.

NI PXI supports various environments, between them also Microsoft Windows XP, which we used to build our software system. The NI PXI controller must completely support the chosen operating system in the selected environment. The controller also supports the most diffused APIs as Microsoft and Borland C++, LabView, etc. PXI requests also that all peripheral modules have the appropriated devices drivers, which must operate in the chosen environment.

3.5 Software environment

The manikin control system was built in the C++ programming language. Fig. 5 shows the measurement flow chart in real time. The system user can communicate with the software and hardware system in the graphical user interface. At the beginning the user has to define and configure the measurement. After the measurement starts the software communicates with the hardware through the NI PXI platform. From the acquired temperature sensors data and previously defined temperature references, the software algorithm controls the heaters. The software algorithm also controls through the NI PXI platform the pumps, which control the sweating glands in order to reach the desired sweating of the foot. After every sampling time the control process is repeated. The measured data are calculated and displayed on-line. The measurement stops automatically when some defined reference condition is reached or the process is stopped manually.

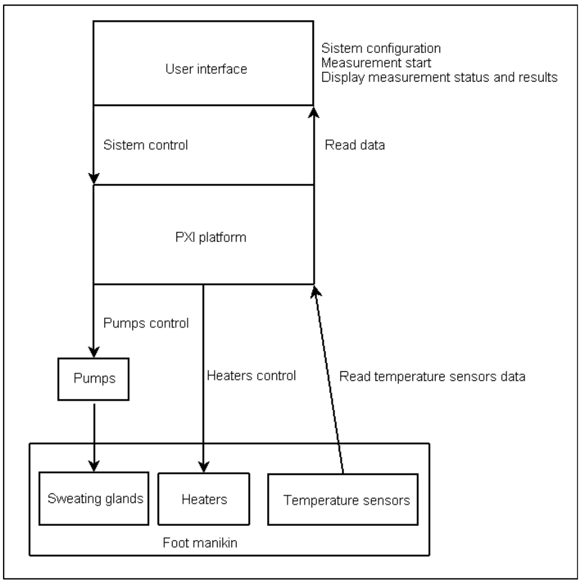


Fig. 5 Diagram of the measurement process

4 Measurement results

4.1 System check up

We have done some reference tests to check the system behavior and to compare our manikin with other manikins. For this reason we did four tests with bare foot, sock, rubber boot and winter boot. We put the manikin in a climatic chamber on temperature $T_A = 15$ °C, relative humidity $RH_A = 50$ %, without wind. We did dry test with foot reference temperature set to $T_F = 35$ °C. Test duration was 90 min, each test was repeated twice. The manikin result tests were checked and compared to the results from other laboratories manikins, which results were described by Kuklane et al. [10]. The test results are shown in Tab. 1.

Tab. 1 Comparison of thermal insulation derived for bare foot, sock, rubber boot and winter boot. Results are compared to those reported by Kuklane et al. (2005).

Wear	Measured $I_M\left[m^2K/W\right]$	Reference $I_R\left[m^2K/W\right]$
Bare foot	0.084	0.090
Sock	0.112	0.120
Rubber boot	0.139	0.170
Winter boot	0.189	0.225

From Tab. 1 we can see, that the thermal resistance increases, as expected. Values increase with more thermally insulated footwear. The values are near the mean values of other manikin's tests described in [10]. The results for bare foot and sock are near the mean values in [10], meanwhile for rubber boot and winter boot the values are lower than the expected values. The main reason was that the wear did not fit the foot well, which cause lose of power heat. We repeated all the tests twice and the differences in the results were around $\Delta I = \pm 0.005\ \mathrm{m^2K/W}$, which is the system accuracy and depends on the accuracy of sensors, program timers, etc.

4.2 Wind influence

We did some test to study the response of the foot manikin in the presence of wind. We simulated the wind with a fan. The results are shown in Fig. 6 and Fig 7. The green line shows the time when the fan was turned on.

From Fig. 6 we can see that the thermal resistance decreases, because the wind is cooling the foot and the regulator needs to increase the given power, to keep the foot on the same temperature. The curves are closer together, because the wind takes heat equally from the foot surface.

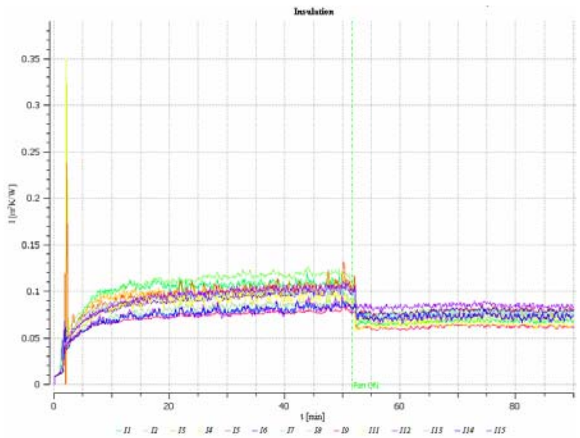


Fig. 6 Influence of wind on insulation (sock)

From Fig. 7 we can note that the heat flux increase, because the wind is cooling the foot and the regulator needs to increase the given power, to keep the foot on the same temperature. The relation between thermal resistance and heat flux is inverse proportional.

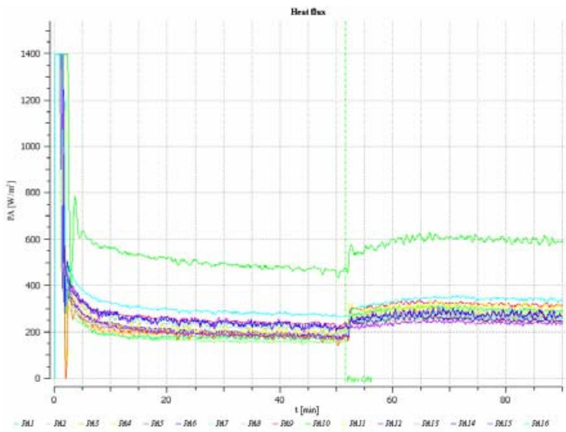
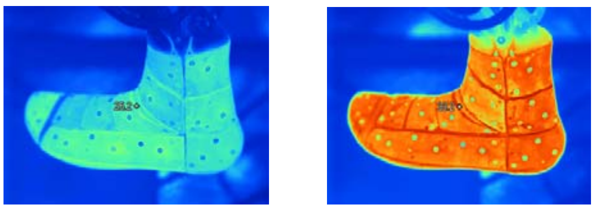


Fig. 7 Influence of wind on heat flux

4.3 Studying the characteristics with infra-red camera

Fig. 8 shows two pictures obtained with infra-red camera when the foot is heated from 15 °C to 35 °C. Fig. 8 a shows the foot at the temperature near 25 °C, in Fig. 8 b the temperature is around 35 °C, which is the stationary state.

Fig. 8 shows that the segments are heating homogenously. Leg is filled with silicone rubber inside which mechanically connects segments together. Silicone rubber is transmitting warmth from one segment to another (dark red lines between segments Fig. 8 b). For an accurate analysis of the system we could treat the system as a multivariable system, what could increase the difficulty of system analysis, control and calculations. We try to construct our next manikins in such a way that segments are connected together mechanically with some holders. So they will be inside hollow, what will presumably reduce the heat transition between segments.



a) b)

Fig. 8 Infra-red thermograms of the foot manikin at a) 25 °C and b) 35 °C

5 Conclusion

We present a device for footwear quality estimation and physiologic simulation of the human foot. The system calculates the thermal and evaporative resistance to estimate the quality of the footwear. The manikin can simulate thermal behaviors of the foot and sweating of the foot. There are many built-in functions for control of the foot heating and sweating.

The device construction, control system and the thermal resistance measurement are presented. Sixteen segments compose the foot manikin. Each segment is an autonomous part, in the sense of construction, control and calculation.

The goal of using segments is that with segments we can find which part of the footwear are worse qualities, what is the base information for the manufacturer and user.

The test results are comparable with manikins from other laboratories.

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