Static and Dynamic Evaluation of Biophysical Properties of Footwear: The Jozef Stefan Institute Sweating Thermal Foot Manikin System

Igor B. Mekjavic[1], Borut Lenart[1], Miro Vrhovec[1], Martin Tomsic[1], Naoshi Kakitsuba[2], Nigel A.S. Taylor[3] & Howard Oakley[4]
[1]Department of Automation, Biocybernetics and Robotics, Jozef Stefan Institute,
Jamova 39, SI-1000, Ljubljana, Slovenia;
[2]Department of Environmental Science and Technology, Meijo University, Nagoya, Japan;
[3]Department of Biomedical Sciences, University of Wollongong, Wollongong, Australia;
[4]Environmental Medicine Unit, Institute of Naval Medicine, Alverstoke, Hants. P012 2DL, U.K.

Contact person: igor.mekjavic@ijs.si

ABSTRACT

Freezing and non-freezing cold injury occurs predominantly in the extremities, with the feet being at greatest risk. Inappropriate footwear is the main cause for the aetiology of cold injury of the feet. Ensuring that footwear meets minimal biophysical standards is therefore essential in preventing cold injury. The aim of the present project was to design and develop a sweating thermal foot manikin with a gait simulator. The Thermal Foot Manikin System comprises a sweating thermal foot manikin, a gait simulator and a control unit. The foot manikin has 10 segments (big toe, remaining toes, sole, heel, medial foot, lateral foot, instep, anterior ankle, posterior ankle, mid calf) constructed of a silver- copper alloy. Each segment is heated with a 10 W heater positioned between the metal alloy plate and silicone body of the foot. The temperature of each segment is monitored with a PT1000 thermistor also attached to the metal alloy plate. Water is delivered to 6 sweat glands in each of the 10 segments, at a rate ranging from 18 μL/segment/hr to 1.8 L/segment/hr. The water is distributed over the segment surface by a thin cotton layer attached to the segment. Each segment is covered by a water impermeable, but water vapour permeable membrane, ensuring that only water vapour crosses the membrane. The electrical power required to maintain the temperature of the surface of each segment is regulated by the control unit. In this manner, the resistance to water vapour may be determined from each of the 10 segments. By disconnecting the sweat gland activity, the same analysis provides a value of insulation for each segment. The manikin is attached to a gait simulator, which can simulate different stride magnitudes (0.2 to 0.4 m) and walking paces (up to 45 min^{-1}). The gait simulator simulates the heel-to-toe action of walking and also simulates the ground reaction forces during simulated gait of individuals with a mass of up to 125 kg. The manikin also allows biomechanical analysis of footwear during simulated gait. The thermal foot manikin is able to analyse the static and dynamic biophysical properties of footwear in sub-zero environments. The differences in the results obtained in the static and simulated gait mode are due to friction between the foot manikin and footwear, and due to footwear design. In the biomechanical mode, the foot manikin allows the assessment of wear, as well as how such wear affects biophysical properties. The developed thermal foot manikin enables the customer to ensure that appropriate footwear is chosen for a given environment, and gives industry the capability to develop footwear with biophysical properties specified by the customer. Such a strategy in the design and development of footwear for cold and wet environments will reduce the risk of cold injury.

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1.0 INTRODUCTION

Thermal insulation properties of hiking boots are determined solely under static conditions. The action of walking, however, may enhance ventilation of the boot micro-environment and thus cause regional changes in the insulation values. We have previously reported the development of a thermal foot manikin for determining the static thermal insulation value of hiking boots (Mekjavic *et al.*, 2002). The aim of the present study was to incorporate a sweating function in the foot manikin, thus allowing the determination of water vapour resistance, and a gait simulator, which would enable the determination of thermal insulation and water vapour resistance under static (standing) and dynamic (walking) conditions.

2.0 METHODS

The Thermal Foot Manikin System (Fig. 1) comprises a heated thermal foot manikin with sweating function, a gait simulator and a control unit.

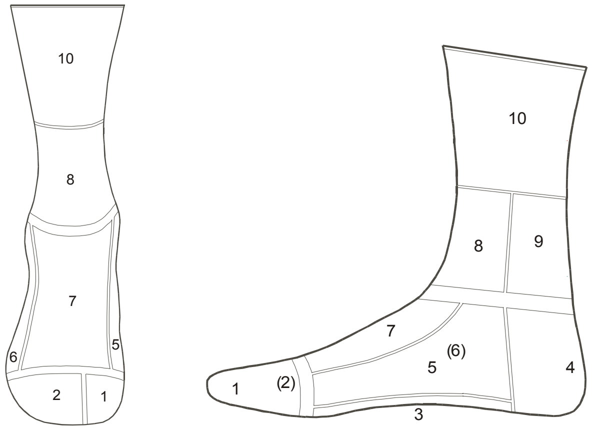
Figure 1: The thermal foot manikin system comprises three components: the Gait Simulator (left), the heated Thermal Foot Manikin (attached to the flywheel of the gait simulator), and the Control Unit (right).

DESIGN

1. Heated Thermal Foot Manikin

The ten segments of the foot manikin are made of silver-copper alloy. Each segment has a heater rated to 10 W (Minco Products Inc., Minneapolis, USA) positioned between the silver-copper plate and silicone body of the foot. The temperature of each segment is monitored by an RTD Pt1000 (Minco Products Inc., Minneapolis, USA) temperature sensor, also attached to the silver-copper plate. The location of the individual segments and their respective surface area are presented in Fig. 2.

The thermal foot manikin comprises two parts. One part contains segments 1, 2, 4, 5, 6, and 7; the second part contains segments 4, 8, 9 and 10. As a result, it is possible to fit the thermal foot manikin very snugly in the appropriate shoe size. Once the first segment is inserted into the shoe or boot, the second segment is slid into place via a metal guide and its position secured by bolting the rod protruding from the foot manikin (see Fig. 2).



No.	Segment	Surface area (cm^2)
1	Big toe	39.6
2	Remaining toes	71.8
3	Sole	97.6
4	Heel	113.0
5	Medial Foot	74.7
6	Lateral Foot	69.2
7	Instep	65.4
8	Anterior ankle	88.3
9	Posterior ankle	82.2
10	Mid calf	257.6

Fig. 2: Diagrammatic representation of the front and side views of the Thermal Foot Manikin. Segments are activated in three possible user-defined combinations: Segments 1 to 7 for testing shoes; segments 1 to 9 for testing hiking boots; segments 1 to 10 for testing boots extending to the mid calf. The surface areas of the individual segments are presented in the table.

2. Sweating Function

Water is delivered to 6 sweat glands in each of the 10 segments, at a rate ranging from 18 μL/segment/hr to 1.8 L/segment/hr. The water is distributed over the segment surface by a thin cotton layer attached to the segment. A moisture content sensor monitors the moisture content of the cotton layer. Valves regulate the flow of water to each segment, ensuring that moisture content is maintained at approximately 80%. Each segment is covered by a water impermeable, but water vapour permeable membrane, ensuring that only water vapour crosses the membrane. The electrical power required to maintain the temperature of the surface of each segment is regulated by the control unit. In this manner, the resistance to water vapour may be determined from each of the 10 segments. Should there be a requirement to evaluate the transfer of "sweat" from the skin surface to the footwear, then both the water vapour impermeable membrane and cotton layer can be removed, allowing direct contact of the footwear with the silver-copper skin containing the artificial sweat glands excreting water to the surface at a desired rate.

3. Gait Simulator

The Gait Simulator simulates a range of walking paces and ground reaction forces. In this manner, the thermal insulation of test footwear may be determined under dynamic (walking) conditions.

Simulation of gait is achieved by the combined actions of a large flywheel, powered by a three phase electric motor, and a pneumatically driven platform (Fig. 3). There are several points of attachment (holes) on the flywheel, varying in their distance from the centre of rotation. These different points of attachment allow the simulation of different stride magnitudes (0.2 to 0.4 m). The simulated walking pace is adjustable, and is determined by the rotation of the flywheel (10 – 45 min^{-1}). During operation, the spinning action of the flywheel raises and lowers the attached Thermal Foot Manikin. Though the thermal foot manikin is attached to the flywheel as a pendulum, its movement is limited by stainless steel guiding rods attached to the pneumatically driven platform. As the foot manikin approaches the mid point of the down phase, it makes heel contact with the metal platform connected to a pneumatic piston. During the latter half of the down phase, the thermal foot manikin pushes down against the metal platform, and causes it to be displaced downwards. The air pressure in the pneumatic piston determines the force exerted on the footwear by the platform, and therefore determines the simulated mass (24 to 125 kg) of the wearer. As the flywheel continues to spin around, it causes the heel to be lifted and the pressure to be exerted by the sole and finally by the toes. The combined rotation of the flywheel and constant pressure exerted by the pneumatically driven platform simulate the heel-to-toe action of walking and also simulate the ground reaction forces during such simulated gait.

The Gait Simulator may also be operated independently of the Thermal Foot Manikin Control Unit. In this mode, the durability and biomechanical properties of footwear may be tested.

Figure 3: Simulation of gait is achieved by the combined action of the flywheel and pneumatically driven platform (see text for details).

4. Control Unit

The control unit maintains the temperature of the segments at the desired levels with National Instruments (Austin, TX, USA) Fieldpoint hardware and LabView software. To maintain the segment temperatures, the individual heaters are activated at discrete time intervals. The power to each segment heater is always identical (10 W). Within any time interval, power to a segment is determined simply by the cumulative time the heater was activated. The user defines the segment set-temperature and segment surface area.

Segmental insulation of footwear is calculated by the LabView software according to the following formula:

$$I\ (°C.m^2.W^{-1}) = \Delta T \times A / P \qquad (1)$$

where,

I = insulation (°C.m^2.W^{-1}).

ΔT = difference in temperature (°C) between the segment surface and temperature of the surrounding medium (either air or water).

P = electrical power (W) required by segmental heaters to maintain the temperature of the copper plate constant, and at the desired level.

Values of insulation are tabulated online, and the programme automatically stops, once measurements of insulation vary by less than 0.01 °C.m^2.W^{-1} between measurements at any given site, for all sites.

EVALUATION

The evaluation of the Thermal Foot Manikin System comprised two parts:

1. The thermal foot manikin was evaluated by comparing the values of insulation obtained for a test hiking boot with the thermal foot manikin with those determined according to the following equation:

$$I\ (°C.m^2.W^{-1}) = \Delta T / Q \qquad (2)$$

where,

Q = heat flux (W.m^{-2}).

Heat flux was measured with Concept Engineering Heat Flux Transducers (Old Saybrook, CN, USA), attached to the individual segments with Tegaderm polyurethane transparent dressing (St. Paul, MN, USA) tape.

Once the thermal foot manikin was inserted in the test boot, the boot was wrapped in a plastic bag and immersed in a bath of water maintained at 15°C for 30 min. During this time the segmental temperatures were maintained at 35°C (EN 344, 1992) and heat flux from the segments stabilised.

2. The static and dynamic insulation properties of two prototype hiking boots were evaluated in 15°C ambient air, while maintaining segmental surface temperature at 35°C.

The insulation values were measured at 1-minute intervals.

The choice of segmental and air/water temperatures for the evaluation tests was based on the recommendations of EN 344 (1992), that surface temperature be maintained between 30 and 35°C and that the surrounding medium be at a temperature 20°C lower than the surface/segment temperature.

3.0 RESULTS

The results of the evaluation trial are presented in Fig. 4, and indicate close agreement of the values of insulation based on the two methods. The insulation values ranged from approximately 0.1 °C.m^2.W^{-1} for the toe and instep to 0.25 °C.m^2.W^{-1} for the sole. These values of insulation were determined statically.

The effect of simulated gait on insulation properties of hiking boots was determined in a subsequent test of two prototype hiking boots. The insulation value was determined using the Thermal Manikin System only, thus calculating insulation based on the electrical power requirements of individual segments during immersion in 15°C water.

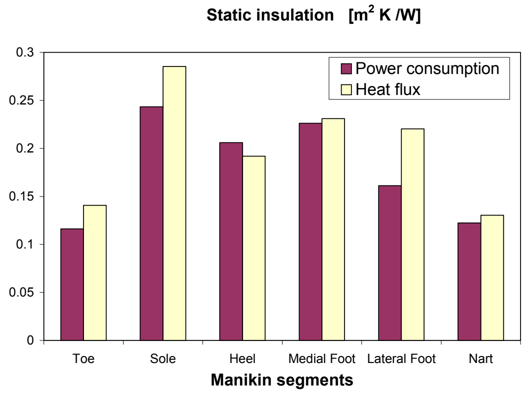


Fig. 4: Unloaded static insulation of test hiking boot determined by either measuring the power needed to maintain segment constant (Power consumption ; equation 1), or measuring the heat flux from each segment (Heat flux ; equation 2).

The results of the static and dynamic evaluation of insulation, presented in Table 1, indicate that for these two hiking boots total insulation increased by 0.2°C.m^2.W^{-1} during simulated gait.

Table 1: Static (unloaded standing) and dynamic (walking) insulation values of two prototype hiking boots.

Test hiking boot	Insulation (°C.m^2.W^{-1})	
	Static	**Dynamic**
Boot A	0.14	0.16
Boot B	0.14	0.16

For both hiking boots the pattern of segmental insulation values was similar to the one observed in the evaluation trial comparing insulation values determined with the Thermal Manikin System and independently with heat flux sensors attached to the surface of individual segments (Fig. 4). To determine to what degree friction and compression of the material caused the increase in insulation during gait, segmental temperature was monitored during simulated gait with the segmental heaters inactive. Segmental temperatures rose by as much as 1°C in both toes segments, the sole and heel. An increase in temperature, albeit not as great, was also observed on the instep and medial and lateral foot.

4.0 DISCUSSION

The developed Thermal Manikin System determines thermal insulation of footwear with the same degree of accuracy as thermal foot models developed by other laboratories (see Kuklane et al., 2003 for review). There has only been one reported attempt of developing a thermal foot model with a gait simulator (Kuklane, 1999), but it could not simulate the mass of an average adult. Our thermal foot manikin has undergone tests lasting 8 hours daily for several days, simulating a 75 kg individual, without any mechanical damage to either the gait simulator or the thermal foot manikin.

We evaluated the Thermal Foot Manikin system with two very similar prototype hiking boots. There was no difference between the insulation values of these boots, but we did observe an increase in the insulation values during simulated gait. The observation of an increase in thermal insulation during gait is in contrast to that reported by Kuklane (1999). Differences between static and dynamic insulation may be due to goodness of fit of the boot, compression of the boot during simulated gait, friction resulting from movement of the foot manikin against the material of the boot. The present thermal foot manikin comprises of two parts, so that it may be inserted in the boot very tightly, thus establishing an extremely good fit in the specified shoe size. The only region, where there may be an air gap is at the sole. This gap is minimised during the stance phase of a stride. Changes in segmental insulation during simulated gait may arise as a consequence of this phasic interaction between a segment and the boot. Most likely, the increase in insulation may be due to heat generated by friction of certain segments with the boot. This was confirmed by the increase in segmental temperatures with the heaters deactivated. Compression due to walking is unlikely to increase insulation but decrease it, thus this is not a likely candidate for the observed gait-induced increase in boot insulation. The thermal foot manikin is therefore a useful tool when comparing different boots or the same boot with different components incorporated in the construction (Endrusick et al. 2000; Rintamäki and Hassi 1989).

Freezing and non-freezing cold injury of the extremities, especially the feet, is a common problem among individuals working and exercising in cold environmental temperatures. The pathogenesis and optimal management of such injuries remains unresolved (Francis and Golden, 1985). However, one of the most critical issues in the prevention of such injuries is the appropriateness of the footwear for the ambient conditions. The Thermal Foot Manikin Systems may become instrumental in the development and evaluation of footwear, and thus preventing the debilitating consequences of cold injury to the feet.

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