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BIOPHYSICAL MODEL FOR HANDWEAR INSULATION TESTING

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Biophysical models of hands, feet and full manikins are used for direct measurement of clothing insulation. In this study, thermal resistance values ($m^2 \cdot K \cdot W^{-1}$) were measured with a weather resistant and simplified 7 zone hand model with upgraded controls and then compared to values from a 22 zone articulated copper model. Insulation is calculated from the power demand required to maintain a selected surface temperature setpoint at a known thermal gradient between the surface setpoint and the environment. For the new model, dry insulation values were 0.21 $m^2 \cdot K \cdot W^{-1}$ for the standard military trigger finger mitten and 0.12 $m^2 \cdot K \cdot W^{-1}$ for the light-duty shell. Values for the 22 section copper hand model were 0.23 and 0.14 $m^2 \cdot K \cdot W^{-1}$, respectively. Both hand models provide replicable measurements of relative total handwear insulation.

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CONTENTS

FORWARD

The purpose of this report is to describe a new biophysical hand model for measuring handwear insulation; to describe the methods used to evaluate the new model; to report and compare handwear insulation values obtained from the new model with values from an articulated, copper hand model.

EXECUTIVE SUMMARY

Biophysical models of hands, feet and full manikins are used for direct measurement of clothing insulation. In this study, thermal resistance values ($m^2 \cdot K \cdot W^{-1}$) were measured with a weather resistant and simplified seven-zone hand model with upgraded controls and then compared to values from a 22-zone articulated copper model. Insulation is calculated from the power demand required to maintain a selected surface temperature setpoint at a known thermal gradient between the surface setpoint and the environment. For the new model, dry insulation values were 0.21 $m^2 \cdot K \cdot W^{-1}$ for the standard military trigger finger mitten, and 0.12 $m^2 \cdot K \cdot W^{-1}$ for the light-duty shell. Values for the 22-zone copper hand model were 0.23 and 0.14 $m^2 \cdot K \cdot W^{-1}$, respectively. Both hand models provide replicable measurements of relative total handwear insulation.

INTRODUCTION

Static thermal manikins are commonly used for clothing testing (Wyon, 1989). Less common are similar biophysical models for testing hand and foot wear (Elnäs and Holmer, 1983; Santee and Endrusick, 1988). The term "biophysical" is appropriate for these models because the models are anthropomorphic and the temperature set points are within normal human ranges. The shape is important because these models measure I_t, the total insulation including internal and boundary air layers. Due to differences in surface air flow, greater surface area relative to the heat source, and reflection of radiation from adjacent body surface areas, the rate of heat loss from complex, curved shapes (such as hands) differs from the rate of heat loss from flat plates (Gonzalez, 1988).

Insulation is the non-directional resistance to heat exchange, but heated models only work when the ambient temperature is lower than the model surface temperature. The rate of heat loss is altered by dressing or insulating the model with different clothing items. An increase in insulation or thermal resistance results in a reduction in the rate of heat loss from the model to the environment. In this study, thermal resistance values ($m^2 \cdot K \cdot W^{-1}$) were measured with a weather resistant seven-zone hand model with upgraded controls, and then compared to values from a 22-zone articulated copper model.

Numerous innovations in cold weather clothing, including radiant barriers, "breathable" moisture barriers, microfiber insulation and improved "wicking" (transport of moisture away from the skin surface), have been introduced in the last fifteen years. The alleged benefits of these innovations have been aggressively promoted by private industry, and considerable pressure is exerted by the public and from within the military to adopt these new technologies and constructions to achieve that elusive goal, comfort in the cold. The new clothing items are often expensive; may lack durability or are otherwise unsuitable for military use; and the alleged benefit may be overstated or even nonexistent. Some technologies, however, may represent a significant improvement which will enhance the individual soldier's work performance and/or comfort in cold environments.

Limited issue or other field trials are the final definitive tests for any handwear, but field conditions are unpredictable and uncontrollable. In field trials without direct monitoring of subject skin surface temperatures, the only "feedback" is statistical evaluations of opinion surveys and reported incidents of cold injury. If an item of protective clothing with serious functional flaws were issued in sufficient quantities for adequate testing under field conditions, the number of personnel exposed to potential injury would be unacceptable. At present, dry insulation values of hand- and footwear are used to eliminate candidate items which do not meet selected levels of cold protection.

An alternative to evaluating clothing by assessing casualty figures is to conduct limited, controlled environmental testing (Santee, et al., 1988, 1990a, Gonzalez, et al., 1989, Endrusick, et al., 1992). Human testing, conducted in environmental chambers under severe conditions, will expose gross inadequacies of new clothing if the correct questions (i.e., environmental conditions and test scenarios) are incorporated into the study. However, if human testing was the only practical method for clothing evaluation, the number of human tests required to separate functional from non-functional clothing technologies and the attendant risks to the test subjects would be unacceptable. Although chamber testing is carefully monitored and controlled, the relatively severe climate conditions selected to maximize exposure significantly increase the risk to the subjects relative to normal field use and conditions. If new clothing items are to be evaluated, developed and delivered to the field in a timely and efficient manner, other biophysical test methods and/or modeling which do not require the participation of human test subjects must be utilized.

US Army Research Institute for Environmental Medicine (USARIEM) has utilized several hand models including single-circuit and zonal models to evaluate handwear. The most complex of these is a 22-zone articulated copper hand. During recent use (c. 1987), difficulties were experienced with that hand control system, and the hand was operated by inputting a constant heating power and operating the hand in a constant environment until the system was in equilibrium. The surface temperatures at equilibrium were then measured and used to calculate the insulation of the handwear (Equation 1). In this study, thermal resistance values ($m^2 \cdot K \cdot W^{-1}$) were measured with a weather resistant, seven-zone aluminum biophysical hand model. The aluminum hand model is a simplified, field portable device which incorporates an improved control system relative to the 22-zone copper hand model.

MATERIALS AND METHODS

MODEL

The hand model was developed from USARIEM performance specifications and fabricated by Northwest Measurement Technology (Seattle,WA). There are three components to the system: the actual hand model with base and sensors; a control interface box which operates the heaters and relays sensor data to the controller; the controller consisting of a personal computer (PC) and several control programs (O'Neill and Bryar, 1990).

As described by the company, the hand is an aluminum casting made from the mold of an actual human hand with sufficient detail to show some fingerprints. It is virtually impossible to fit the correct size of handwear over a rigid hand model with abducted (spread) fingers. An important design requirement was some mechanism for adjusting the model to mount proper sized handwear without cutting or otherwise modifying the handwear. Handwear cannot be fitted over a completely rigid model unless it is oversized; altered by opening seams, or by other stress relief.

The new aluminum hand model was initially evaluated to determine the reliability of the surface temperature set point controls. Thermocouples were placed on the surface of the model to determine if the control set points for surface temperature matched measured temperatures, and were stable inside a temperature controlled chamber. The model was tested both bare and with handwear fitted to the model. An important modification was the placement of the thermistors. After the initial evaluation, the manufacturer modified the placement of the thermistors. Rather than being placed inside the finger core against the aluminum, holes were bored through the sections so that the thermistor bead is exposed to the air through a hole and the beads are level with the surface of the hand. In effect, although inserted from inside, the sensors are countersunk to the surface of the hand, and the temperature at the hand/air interface is measured rather than inner temperatures of the model. The hand was spray painted flat black (wrought iron flat black spray enamel #1400514, Sherman-Williams, Co, Cleveland, OH) to obtain an emissivity (ε) approximating 0.98.

The original control system utilized an AST Premium/286 computer (AST Research, Inc., Irvine, CA) with modified output. A subsequent system upgrade which utilized a 386 microprocessor and an Intel math co-processor is described later in the paper. The control program was written with commercial software (LABTECH Notebook, Laboratories Technologies Corporation, Wilmington, MA). The software allows the user to modify the control program rather than relying entirely on the original programming developed by the design group. Such variables as individual section set point and voltage gain rates can be modified; although it does require some operator expertise to alter the program. Documentation, parts lists, schematics and an instruction manual were provided by the manufacturer. The USARIEM aluminum hand was the first physical model produced by the manufacturer.

CALCULATIONS

Insulation (I_i) for handwear zones are calculated from the power demand (P_i) required to maintain each hand model section at a selected constant set point (T_s) in a test environment maintained at a constant temperature, (T_{ch}). The basic relationship is:

$$P_i = h_{c+r} \cdot A_i \cdot \Delta T_i$$
$$I_i = h_{c+r}^{-1}$$
$$I_i = A_i \cdot \Delta T_i \cdot P_i^{-1}$$

Insulation (I) or thermal resistance is the reciprocal of the combined heat transfer coefficient (h_{c+r}) for convective (c) and radiative (r) heat transfer. P_i is calculated from the measured voltage draw and the resistance of heater strips for each section. ΔT_i

is the temperature gradient between the section surface set point and the chamber temperature. The equation for total insulation (I_T) can be simplified if ΔT_i is a constant difference (ΔT) for all sections.

$$I_T = \Delta T \cdot \Sigma [A_i \cdot (A_T \cdot P_i)^{-1}]$$

A_i is the area of the individual hand model section and A_T is the total area of the seven model sections. Total insulation for a test handwear item (I_T) is calculated as the area weighted average of the seven individual model sections. The initial software and control program for the hand model provided printouts of power consumption and surface temperatures. A FORTRAN program using model surface areas was written to calculate I_T from these parameters. The two wrist sections act as a guard zone and are not used to calculate handwear insulation. I_T includes the insulation provided by a thin boundary area of air (I_a). The intrinsic insulation of the clothing (I_{clo}) can be calculated by subtracting the air layer insulation (I_a) from I_T (Gonzalez, 1988).

An alternative method to the weighted average approach for calculating I_T is to calculate the slope of total power demand at different test chamber temperatures for all seven hand sections. The advantage of the latter method is that it compensates for any effects due to heat exchange between sections.

MODEL AREA

To calculate insulation from power demand, the sectional surface areas must be known. The method used was to cover the hand surface with paper tape; remove the tape, and spread it out into a flat pattern. That pattern was then traced onto graph paper with a small scale grid. Individual grid areas were then summed, and the method was repeated. Other methods (weighing paper cut outs and calculating areas from hand dimensions) were used to establish that the values obtained by the grid method were valid.

TEST METHOD FOR DRY INSULATION

To obtain data for calculating the stability of the model at different air temperatures, the model was run, with or without handwear, at a given chamber setting until stable; then the chamber temperature was raised or lowered as data continued to be collected. The temperature set point can be independently selected for each model section, but to reduce heat exchange between hand sections, all sections were set at 30°C (86°F). The temperature gradient was therefore a constant for these tests for each chamber temperature set point.

RESULTS

Dry insulation values for the new model were 0.35 $m^2 \cdot K \cdot W^{-1}$ for the arctic mitten set; 0.21 $m^2 \cdot K \cdot W^{-1}$ for a standard military trigger finger mitten, and 0.12 $m^2 \cdot K \cdot W^{-1}$ for the light-duty shell glove. Values for the 22-zone copper hand model were 0.37, 0.23, and 0.14 $m^2 \cdot K \cdot W^{-1}$ respectively. Values for the bare models without handwear were 0.04 (aluminum) and 0.06 (copper) $m^2 \cdot K \cdot W^{-1}$. Table 1 presents values for the bare hand, issue military handwear and one prototype. Insulation values calculated from the slope of power demand for the aluminum model were comparable (bare hand = 0.05 $m^2 \cdot K \cdot W^{-1}$, LD = 0.12 $m^2 \cdot K \cdot W^{-1}$, trigger finger = 0.21 $m^2 \cdot K \cdot W^{-1}$ and arctic = 2.27 $m^2 \cdot K \cdot W^{-1}$). Table 2 compares the results of the two calculation methods. Figure 1 illustrates the total power demand for three types of standard issue military handwear at different temperature gradients.

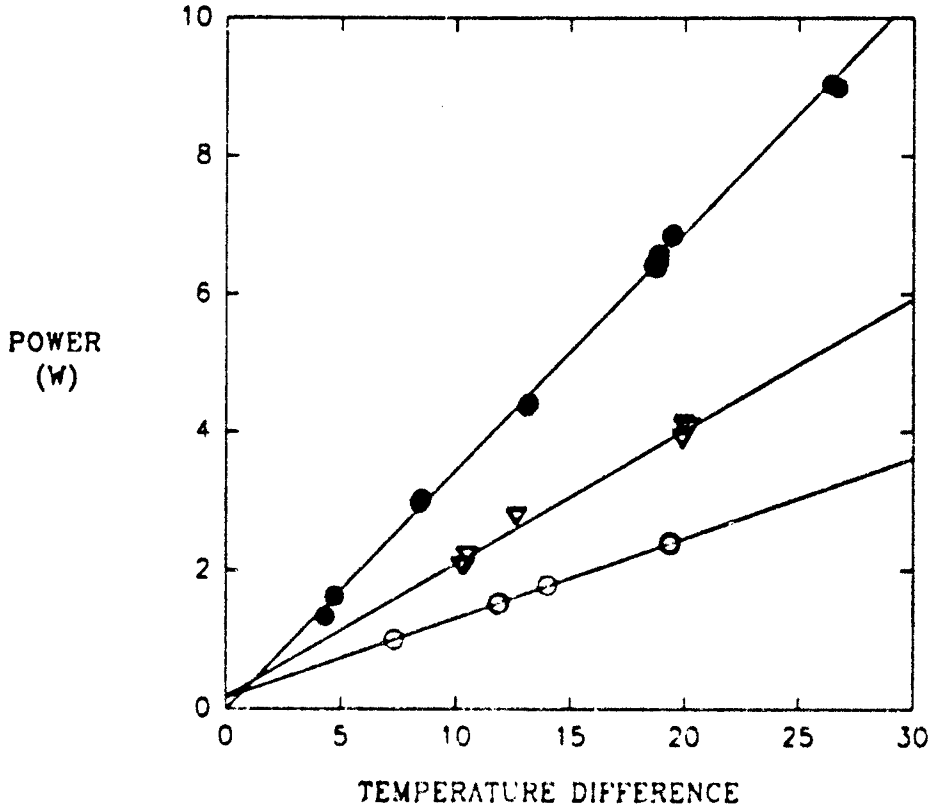
Table 1. Insulation values for selected handwear evaluated on two USARIEM biophysical hand models

handwear	22-zone copper model $m^2 \cdot K \cdot W^{-1}$ (clo)	7-zone aluminum model $m^2 \cdot K \cdot W^{-1}$ (clo)
bare hand	0.06 (0.4)	0.04 (0.3)
arctic mitten set	0.37 (2.4)	0.35 (2.2)
trigger finger mitten	0.23 (1.5)	0.21 (1.3)
light-duty glove	0.13 (0.9)	0.12 (0.8)
vehicle crew glove	0.16 (1.0)	0.16 (1.0)

Table 2. Insulation values for selected handwear calculated from power demand slopes and summation of zone insulation

handwear	zone calculation method $m^2 \cdot K \cdot W^{-1}$ (clo)	slope calculation method $m^2 \cdot K \cdot W^{-1}$ (clo)
bare hand	0.04 (0.3)	0.05 (0.3)
arctic mitten set	0.35 (2.2)	0.35 (2.3)
trigger finger mitten	0.21 (1.3)	0.21 (1.4)
light-duty glove	0.12 (0.8)	0.12 (0.8)

Figure 1 illustrates the relationship of the difference between chamber air temperature to power demand for standard military handwear. The slopes of the lines are directly proportional to the rate of heat loss from the entire hand model. The symbols are (○) for the arctic mitten set; (▽) for the trigger finger mitten, and (●) for the light-duty glove.



MANUFACTURER'S UPGRADE

After delivery of the USARIEM model, U.S. Navy Clothing & Textile Research Facility (NCTRF) purchased a hand model from the same source (Northwest Measurement Technology). The Navy model incorporated an extension of the wrist section for the testing of handwear with long gauntlets (10 sections plus guard area) and improved software (O'Neill and Bryar, 1990). In a subsequent upgrade of the software for the USARIEM model based on the Navy model, a new control program was provided by the company, and the supporting computer hardware was also upgraded (Gateway 386/33C, Gateway 2000, North Sioux City, SD). The new software calculates handwear insulation internally. The differences found in insulation values for the standard handwear may be attributable to larger model areas. Similar changes were obtained by recalculating total insulation after increasing the total surface area by 10% to compensate for space between model sections (Santee and Chang, 1990).

UPGRADE RESULTS

Table 3. Insulation for selected handwear using upgraded software

handwear	22-zone standard	upgrade
bare hand	0.06 (0.4)	0.05 (0.3)
arctic mitten set	0.37 (2.4)	0.35 (2.2)
trigger finger mitten	0.23 (1.5)	0.21 (1.4)
light-duty glove	0.14 (0.9)	0.13 (0.9)

CONCLUSIONS

The minimal differences in I_T values for the two models are likely attributed to the difference between the natural "relaxed" posture of the copper hand and the rigid, abducted, (almost hyperextended) aluminum hand. When the same handwear is fitted over both models, there are thicker insulating interior air spaces formed over the copper model, especially in the palm region.

It should be emphasized that the differences are apparently due to difference in "fit". A particular manufacturer's standard "large" sized handwear may fit the hand model better than another manufacturer's handwear, thereby resulting in slightly different insulation values. The same problem is inherent to all measurements of clothing insulation on physical models. Even greater differences might be expected in fit when standard sized clothing is worn by non-standard sized humans.

When measured values are used to represent "absolute" insulation, as might be required for input into a analytical model, a difference of 0.02 $m^2 \cdot K \cdot W^{-1}$ is probably less than would actually result from differences in fit between individuals. Insulation measurements derived from either hand model are correct in the sense that both hand models provide replicable measurements of relative total handwear insulation which allow discrimination in relative insulation levels between different handwear.

The results are utilized as a relative ranking in relation to other candidate clothing and/or the standard control clothing. Because of the stable, consistent nature of biophysical model data, virtually any difference is statistically significant. Factors such as glove to model fit which have no established bearing on human performance, can result in a statistically significant difference between handwear prototypes. If statistical significance rather than relative grouping is used as the selection criterion, the user may be lead, by the "significance" of the difference between handwear to select one glove over another. From a pragmatic perspective, once the insulation data establishes that the prototypes meet the necessary criterion for insulation relative to the standard handwear, other factors, such as bulk, cost and durability should take precedence over insulation.

It is actually more proper to group candidates relative to standard clothing than to assign an exact rank based on very small, but statistically significant, differences. In practice, there are three levels of classification relative to the control or standard glove: gloves within 10% of the standard handwear (equivalent); handwear with insulation that is lower than the standard by more than 10% (rejection), and gloves which exceed the standard by more than 10% (superior).

Finally, the utility of the more rugged hand model could be utilized in other ways. The original USARIEM specifications required a model which was water-resistant and could be used in an outdoor environment. Preliminary work has been conducted to test wet handwear by plotting the decrease in power demand as the handwear dries. As originally planned, the model could be deployed as a sensitive field environmental sensor which would actually measure the heat loss to the environment experienced by the deployed soldiers. The heat loss to the environment is analogous to the "cooling power" calculated for the Wind Chill Index (Siples and Passel, 1945) except that the hand model measures the heat loss in relation to the actual level of handwear protection and the specific geometry of the hand. On a more practical level, model power demand can be correlated to the potential for hand cold injury, discomfort or inability to maintain hand function.

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