Santee WR, Berglund LG, Cardello A, Winterhalter CA, Looney DP, Gonzalez JA, & Potter AW. Physiological assessment of Soldiers wearing military uniforms of different fabrics during intermittent exercise. J Sport Human Perf 2020; 8(1):1-14.
DOI: https://doi.org/10.12922/jshp.v8i1.167

JOURNAL OF SPORT AND HUMAN PERFORMANCE

ORIGINAL RESEARCH OPEN ACCESS

PHYSIOLOGICAL ASSESSMENT OF SOLDIERS WEARING MILITARY UNIFORMS OF DIFFERENT FABRICS DURING INTERMITTENT EXERCISE

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ABSTRACT
Quantifying the relationship between the physical properties of clothing worn at or near comfortable conditions to the wearer's physiological responses is of significant interest to a broad range of users and developers. This study developed and evaluated methods for quantifying these relationships. The physiological responses of nine healthy Soldier Volunteers (1 female, 8 males) (23 ± 4 yr; 174.2 ± 5.8 cm; 73.4 ± 6.5 kg; 17.90 ± 3.99% body fat) were collected and analyzed during sitting (rest) and activity. Soldiers repeated four chamber trials while wearing four uniforms of the same design, but with different material properties. The thermal and evaporative resistances and physical properties were evaluated for each ensemble prior to testing. During each trial, Soldiers alternated walking on a treadmill at 1.34 $m \cdot s^{-1}$ (3 mph) for 30 minutes, then sitting for 10 minutes. That test sequence was repeated four times, for a total of 170 min. Testing was conducted in a climatic chamber at two environmental conditions: a neutral condition (NC) with an air temperature (T_a) of 20°C, relative humidity (RH) of 50%, wind velocity (V_w) of 1.1 ms^{-1}; and a warm humid (WH) condition (27°C, 75% RH, V_w 1.1 ms^{-1}). Minute-by-minute measures of rectal temperature (T_{re}) were collected, along with continuous measures of relative humidity under clothing (RH_{uc}), and skin temperature (T_{sk}) measured at 3 sites. Total body temperature (T_b) was calculated from T_{re} and mean T_{sk} ($\bar{T}_{sk}$). Skin wettedness (ω) was calculated from RH_{uc} and T_{sk}. Although there were a few overall significant differences ($\alpha \leq 0.5$) for T_{re}, T_{sk}, T_b, RH_{uc} or ω, post hoc testing (Tukey's Studentized Range Test, $\alpha \leq 0.5$) indicated no significant differences between any two garments. Results for sweating, water loss and retention in clothing for the NC (20°C) environment were not significant. For the WH (27°C) environment, differences for sweat retained in clothing (Sw_{cl}) were significant between the wool garment and each of the other 3 garments. Between clothing fabric types there was also significant difference in the rate of evaporative water loss. (R_{ev}).

Keywords: skin wettedness; sweat response; body temperature; skin temperature

INTRODUCTION

Quantifying the relationship between the physical properties of clothing worn at or near comfortable conditions to the wearer's physiological responses is of significant interest to a broad range of users and developers. This study obtained both clothing data and measured physiological responses of test Volunteers wearing four different military uniforms made from permeable fabrics that differed in physical and sensory properties. It is understood these properties may influence the perception of thermal and tactile comfort sensations experienced by Soldiers while wearing these garments and may also influence the physiological responses. This paper addresses the physiological responses of the test volunteers to the different uniform treatments.

The thermal state of an individual is determined by a combination of environmental exposure, and certain "personal" factors [1] such as clothing, posture, activity level and internal physiology [2-3]. Relative to an individual's thermal state, and ultimately Soldier readiness and mission performance, there are three main concerns: comfort, function and survival. As stress increases, the dominate condition or zone degrades from a benign state of comfort to a state where the only focus is on survival. Comfort is a subjective condition often addressed from two perspectives – thermal comfort and the broader construct of psychological comfort. A condition of thermal discomfort generally precludes a perception of psychological comfort. In contrast to many military clothing studies, the test environmental conditions selected for this study are relatively benign, but when combined with moderate exercise, could induce discomfort and physiological strain. However, that perception may be altered if the activity, such as jogging, is often associated with a degree of thermal strain. Given that a degree of thermal strain, such as warmer skin temperature, is anticipated while jogging, and thus is an accepted factor in an activity, psychological discomfort during those activities may be more identified with clothing factors such as roughness or friction. Thermal comfort may be easier to define than overall psychological comfort as it may be related to more readily measurable physiological responses such as thermoneutrality or skin wettedness.

Functional zones may overlap both comfort and survival. However, within the functional zone, there may be sufficient thermal stress to impact physiology (cause thermal strain). If individuals are able to compensate and still perform activities without significant impairment, they are, by definition, in the functional zone. Transition from function to survival occurs when the requirements for thermoregulation interfere with performance and/or body temperature ranges into unsafe hyper- or hypothermic levels. In the survival state, continued exposure may become a threat to homeostasis. Deep body temperature is the best indicator of a threat to survival, as thermal balance is the immediate concern for survival (risk of dehydration, hypothermia or hyperthermia).

METHODS

Participants

Nine (9) healthy Soldier Volunteers were recruited from the Natick Soldier Center and Human Research Volunteer Program**.** Volunteers were briefed on the study and gave written informed consent to participate and expressly assured that they were free to withdraw from participation at any time. Volunteer anthropometrics (mean±SD) for the 9 individuals (1 female, 8 males) were: age (23 ± 4 yr), height (174.2 ± 5.8 cm), weight (73.4 ± 6.5 kg), and percent body fat (17.90 ± 3.99%).

Testing Overview

Body composition was estimated using standard methods for determining body fat from body circumferences, height and weight [4-5]. Testing was conducted in the Doriot climatic chamber located at the Natick Soldier Center, Natick, MA. The complete protocol consisted of eight days of testing conducted in two test environments; a control neutral condition (NC) air temperature (T_a) of 20°C and 50% relative humidity (RH) and a warm humid (WH) condition T_a of 27°C and 75% RH. Wind velocity (V_w) was maintained at 1.1 $m \cdot s^{-1}$ for both environmental conditions.

Volunteers walked on a level treadmill at 1.34 $m \cdot s^{-1}$ for 30 minutes, then sat for a 10 minutes. That sequence of rest and walk was repeated four times on each test date. To minimize Volunteer risks, chamber exposure time was limited to these set test durations. Each Volunteer was tested in one combination of uniform and environment per day for a maximum total exposure time of 170 min. Study activities were stopped if Volunteers reached a rectal temperature (T_{re}) of 38.5°C or a sustained heart rate of 1 min outside of the limits of 75 to 145 bpm during treadmill walking or above 100 bpm while seated. Both T_{re} and local skin wettedness (ω) on the skin surface were continuously monitored. Skin surface temperature (T_{sk}), local RH under clothing (RH_{uc}), and heat flow (HF) were measured on the torso, thigh and forearm. Mean values were calculated using Burton's weighting of 0.50 for the torso, 0.36 for the thigh and 0.14 for the arm [6]. Body temperature (T_b) was calculated by weighting T_{re} by 0.9 and $\bar{T}_{sk}$ by 0.1.

Skin wettedness (ω) is defined as the ratio of the area of water-covered skin to the total skin surface area. It may be estimated from the actual vapor pressure difference across the clothing to the maximum if skin were completely wet [7-8]:

$$\omega = (p_{uc} - p_a)/(p_{s,sk} - p_a) \qquad \text{(Eq. 1)}$$

where the water vapor variables are the vapor pressure under clothing (p_{uc})), saturated vapor pressure at skin temperature ($p_{s,sk}$), and ambient vapor pressure (p_a).

The vapor pressure under the clothing was calculated from the relative humidity under clothing (RH_{uc}) and the saturated vapor pressure at temperature (T_{uc}) under clothing ($p_s(T_{uc})$):

$$p_{uc} = RH_{uc}\, p_s(T_{uc}) \qquad \text{(Eq. 2)}$$

During the seated period between walks, a skin moisture/wettedness/friction test was administered along with comfort related questionnaires [9]. This paper addresses only the physiological responses to the different uniform treatments.

Test Clothing

The study assessed four test uniforms. The test garments were made of a single design from fabrics that differ in physical properties. The garment design used was based on the standard battle dress uniform (BDU) as described in MIL-C-44048 Coats, Camouflage Pattern, Combat, and MIL-T-44047 Trousers, Camouflage Pattern, Combat. Garments were laundered five times prior to testing, and once between each test. Prior to each test day, garments for that day were hung overnight in a conditioning room at conditions of 29°C and 20% RH. To control for problems associated with fit, all Volunteers participated in fitting sessions to ensure the best possible fit within the limits of the prototype size tariff. Test garments were worn over biking shorts, with running shoes, athletic socks and a hook and pile cuff which simulated the blousing of the trousers.

The female test Volunteer wore a sports bra. To increase skin to clothing contact area, no t-shirt was worn and to ensure uniformity, bike shorts and socks were provided for Volunteers to wear every test day.

The four uniform fabrics were based on clothing within the military inventories of the US, Canada, and Australia. Each uniform had similar thermal insulation and water vapor transmission properties but differ in other ways. The fabrics were specifically chosen based on their physical performance characteristics as they relate to comfort such as weight, surface tactility, and wickability. Overall the fabrics weigh in the range of 6.1 to 7.1 ounces per square yard with the exception of the lighter Australian uniform. Detailed descriptions are shown in Table 1.

Test Scenario

Pre-test: Subjects were weighed nude then instructed to insert rectal temperature probe (YSI # 18480 with 400 series #44033) thermistor, Yellow Springs Instruments, Yellow Springs, OH). Heat flow discs (Concept Engineering Disk Heat Flux Transducer with Integral Thermistor, Model #: FR-025-TH44033-F6, Concept Engineering, Old Saybrook, CT) and humidity sensors (Hy-Cal Humidity Sensor, IH-3602C, Honeywell International, Freeport, IL) were placed on the back, arm, and thigh to measure skin surface temperatures. Volunteers were instrumented with heart rate monitors (Polar Beat, Polar Electro Oy, Kempele, Finland) and then dressed in test ensembles. Upon complete dressing and instrumentation, Volunteer total weights were measured prior to entering the test chamber.

Chamber testing: On test days, Volunteers entered the climate chamber and were connected to the data acquisition system. They then sat at rest on a bench for 10 minutes before starting to walk. Volunteers then walked on a treadmill for 30 minutes, sat at rest again for 10 minutes. During each 10 minute pause they were given 150 ml of water to drink. Volunteers each conducted this work/rest/test sequence four times, while wearing each of the test uniforms. Volunteers remained in the chambers for a total of 170 min. During the initial baseline period, and during the resting periods, the clothing-skin friction test was administered and a battery of comfort-related questions administered during both rest and walking [9].

Post-test measurements: Upon exiting the chamber, the Volunteers' post-exercise clothed weights were measured. After undressing and removal of instrumentation they were weighed nude to obtain their post-exercise nude weights. Total water loss was determined from the differences in pre and post nude weights plus weight of water drunk minus urine.

RESULTS

Biophysical Properties of the Clothing

Thermal manikin testing was conducted to obtain values of total insulation (I_T in clo), water vapor permeability (i_m, ND) and an estimate of "cooling power" based on the ratio of i_m/clo (ND) [10-13]. Testing was replicated three times for each washed garment (Table 2). Based on t-tests, small, but significant differences (α=0.5) were found between ensemble properties. Total insulation (I_T) for Uniform D was significantly greater than the other three uniforms (A,B,C), Uniform C was greater than the Uniform A. Uniform B and C had significantly higher values of i_m and i_m/clo than Uniform D. However, there is a difference between statistically significant differences and physiologically significant differences [14-15].

Table 1. Physical and material properties of each test uniform

Uniform A	Uniform B	Uniform C	Uniform D
Australian Army specification 6557	United States Army MIL-C-44436	Canadian National Defence specification D-80-001-098/SF-001 (1989-08-29)	United States Army MIL-C-43842
Australian camouflage pattern	Woodland camouflage printed	solid green color	Woodland camouflage printed
oxford weave, and is made from a blend of 50% cotton, and 50% polyester	blend of 50% nylon (type 420, 1.7 denier per filament), and 50% combed cotton, in a ripstop poplin weave	woven in a plain weave, and is a blend of 65% wool, and 35% polyester	fabric is blend of 92% Nomex, 5% Kevlar, and 3% P140 electrostatic dissipative fiber, in an oxford weave
5.1 ounces per square yard	6.7 ounces per square yard	6.1 ounces per square yard	7.1 ounces per square yard

Table 2. Measured biophysical and physical uniform properties (air velocity =0.4 m/s^{-1})

Uniform	Total Insulation (I_T, clo)	Water vapor permeability index (i_m, N.D.)	Cooling power (i_m/clo, N.D.)	Weight (oz·yd^{-2})	Total Uniform weight (kg)
A	1.31	0.38	0.29	5.1	1.01
B	1.30	0.37	0.29	6.7	1.39
C	1.33	0.38	0.28	6.1	1.18
D	1.34	0.35	0.26	7.1	1.42

Physiological Results

Physiological measurements made during the study of the changes in T_{re}, T_{sk}, humidity under clothing (%RH_{uc} and ω), net water loss, evaporative water loss and sweat retention in clothing are summarized in Tables 3 and 4 and shown graphically in Figures 1-9.

Results for the measured water loss and evaporation are presented in Figures 7-9 and Table 4. Values for sweating and evaporation were single values derived for the entire test period. The sweating efficiency (%EFF) is calculated as R_{ev}/R_w as a percentage. Net rate of water loss (R_w) is calculated as [(Pre-test nude weight + water) – (post-test nude weight)]/time in g/min. The rate of evaporative water loss (R_{ev}) is calculated as [(Pre-test dressed weight + water) – (post-test dressed weight)]/time in g/min. Both R_w and R_{ev} are presented in Figures 7 (NC) and 8 (WH). The value for sweat retained in clothing (SW_{cl}), in grams, is calculated from (Pre-test garment weight – post-test garment weight). Figure 9 presents values for SW_{cl} for the WH testing. The relatively large variances in the NC setting can be seen in Table 4.

ISSN: 2326-6333

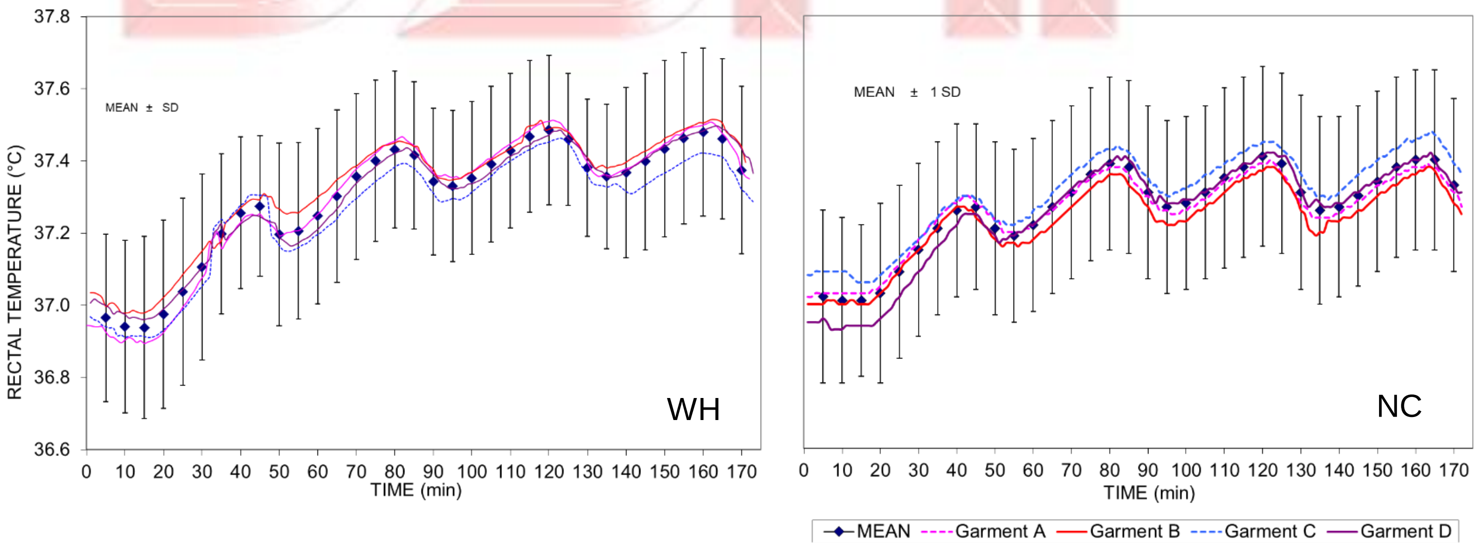
Table 3. Mean, standard deviation (SD) for rectal temperature (T_{re}), change in rectal temperature from baseline (ΔT_{re}), mean skin temperature (T_{sk}), body temperature (T_b), mean percent skin surface relative humidity (RH_{uc}) and mean skin wettedness (ω).

Condition	Thermal Neutral (NC) 20°C, 50% RH				Warm Humid (WH) 27°C, 75% RH			
Uniform	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
T_{re} (°C)	37.3±0.26	37.2±0.24	37.3±0.23	37.3±0.33	37.3±0.27	37.3±0.24	37.3±0.34	37.3±0.25
ΔT_{re} (°C)	0.23±0.20	0.23±0.15	0.22±0.18	0.31±0.19	0.37±0.25	0.33±0.20	0.32±0.21	0.34±0.24
T_{sk} (°C)	31.2±0.82	32.0±0.84	31.6±1.17	32.1±0.61	33.3±0.64	33.0±0.65	33.1±0.80	33.1±0.86
T_b (°C)	36.7±0.24	36.7±0.23	36.7±0.20	36.7±0.30	36.9±0.24	36.9±0.20	36.9±0.28	36.9±0.22
RH_{uc} (%)	43.4±10.7	40.3±7.2	40.3±6.8	40.4±6.6	75.2±13.4	80.2±10.9	78.9±10.5	79.7±10.3
ω (n.d.)	0.18±0.13	0.14±0.08	0.15±0.10	0.14±0.07	0.43±0.18	0.43±0.17	0.44±0.18	0.43±0.17

Table 4. Mean, standard deviation (SD) for percentage of sweating efficiency (%Eff), sweat retention in clothing (SW_{cl}), rate of water loss (R_w), and rate of evaporative loss (R_{ev})

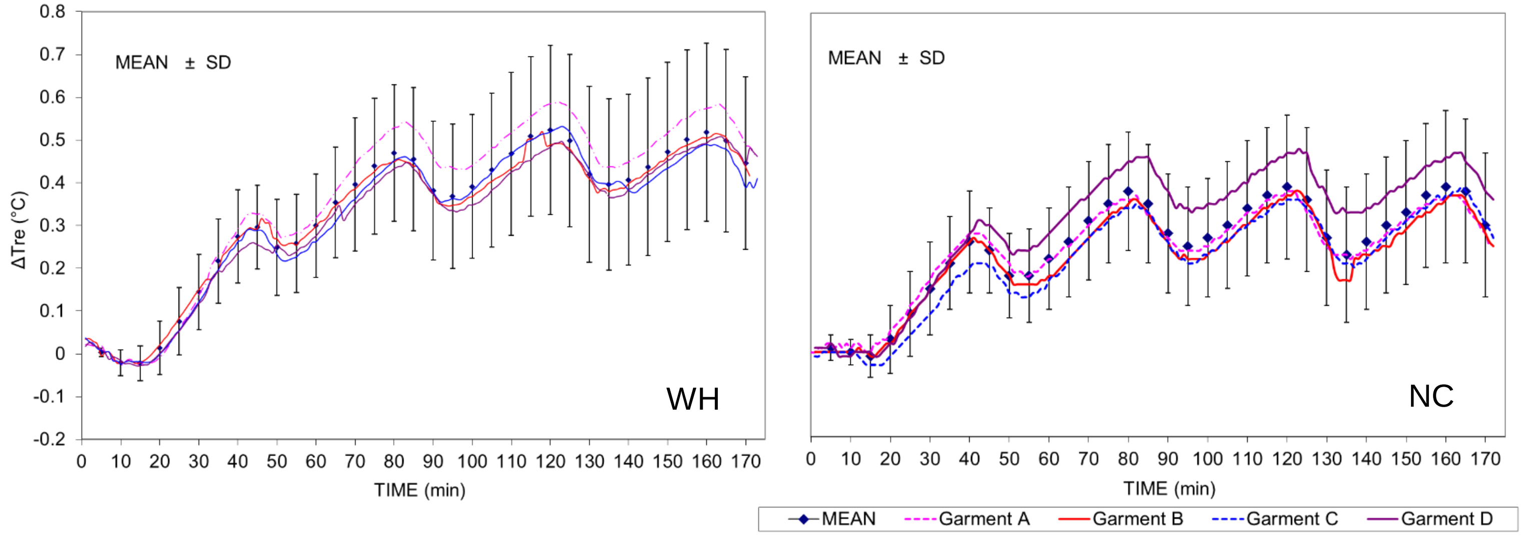
Condition	Thermal Neutral (NC) 20°C, 50% RH				Warm Humid (WH) 27°C, 75% RH			
Uniform	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
%Eff	63.8±27.7	59.9±20.7	63.3±23.8	62.2±25.4	74.5±19.2	71.8±12.1	68.1±16.8	70.8±19.6
SW_{cl} (g)	14.2±16.0	60.5±130.5	55.0±95.2	8.1±5.5	44.8±22.0	52.9±25.7	80.1±22.0	31.7±18.4
R_w (g/min)	3.7±1.5	3.7±1.6	3.7±1.6	4.4±2.4	5.0±1.5	4.4±1.0	5.2±1.6	5.6±1.6
R_{ev} (g/min)	2.0±0.4	2.1±0.8	2.0±0.7	2.2±0.3	3.5±0.5	3.1±0.7	3.4±0.8	3.7±0.8

Figure 1. Mean core (rectal) temperature under warm-humid (Left: WH = 27°C, 75% RH) and neutral (Right: NC = 20°C, 50% RH) conditions.



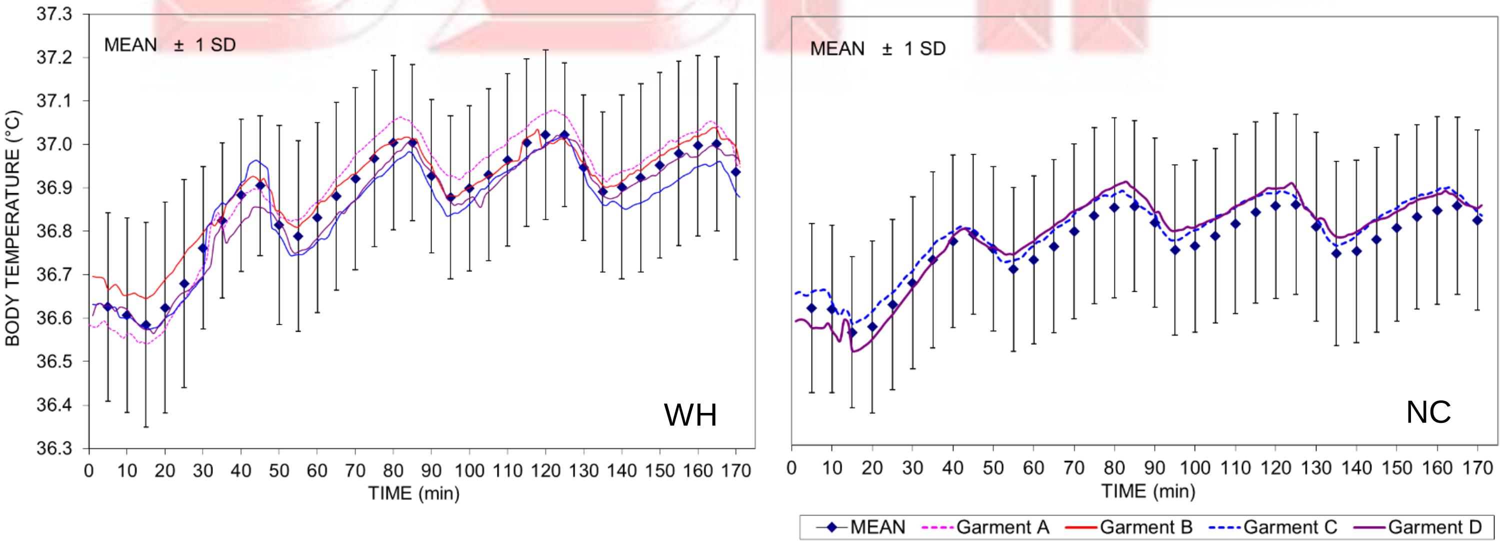
Note: Mean±1 SD values are for all garments and all volunteers.

Figure 2. Changes in mean core temperature (ΔT_{re}) under warm-humid (Left: WH = 27°C, 75% RH) and neutral (Right: NC = 20°C, 50% RH) conditions.



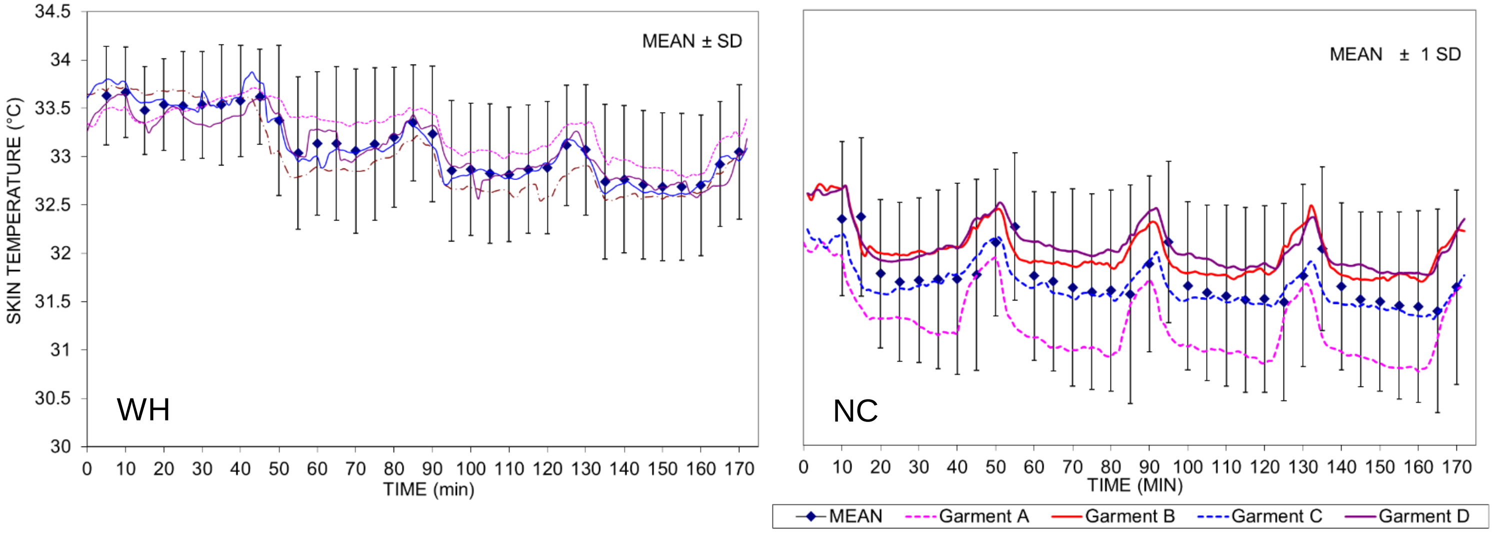
Note: Mean±1 SD values are for all garments and all volunteers.

Figure 3. Mean body temperature ($\overline{T}_b$) under warm-humid (Left: WH = 27°C, 75% RH) and neutral (Right: NC = 20°C, 50% RH) conditions.



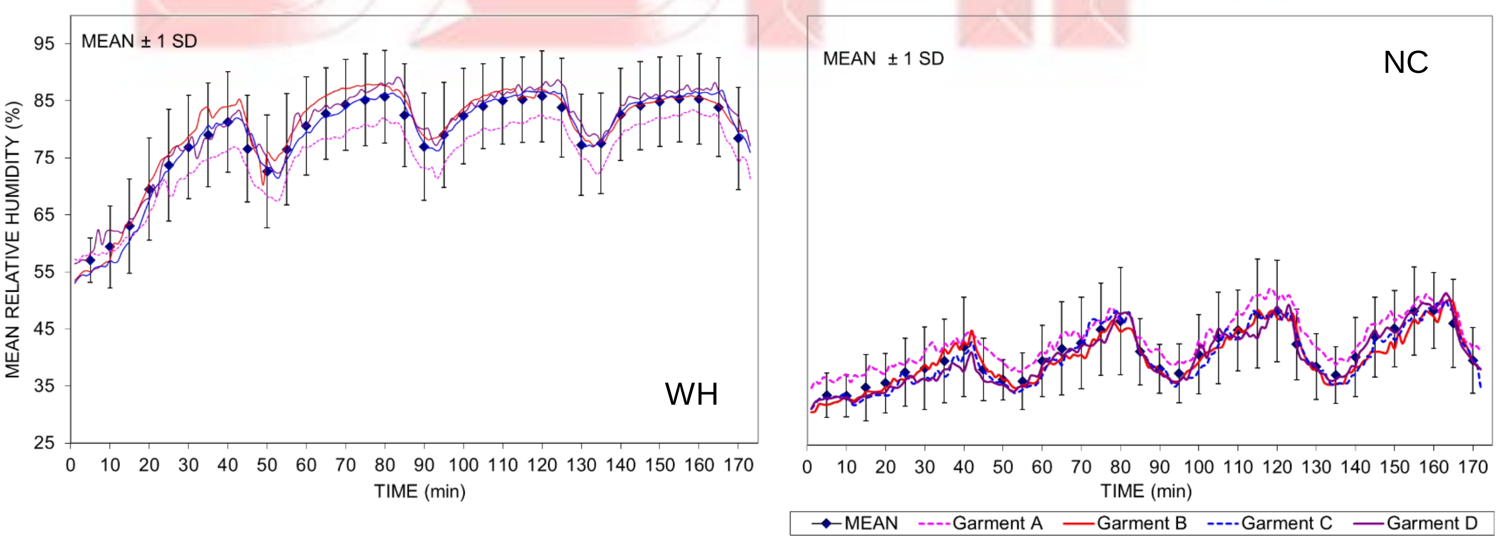
Note: Mean±1 SD values are for all garments and all volunteers.

Figure 4. Mean skin temperature ($\overline{T}_{sk}$) under warm-humid (Left: WH = 27°C, 75% RH) and neutral (Right: NC = 20°C, 50% RH) conditions



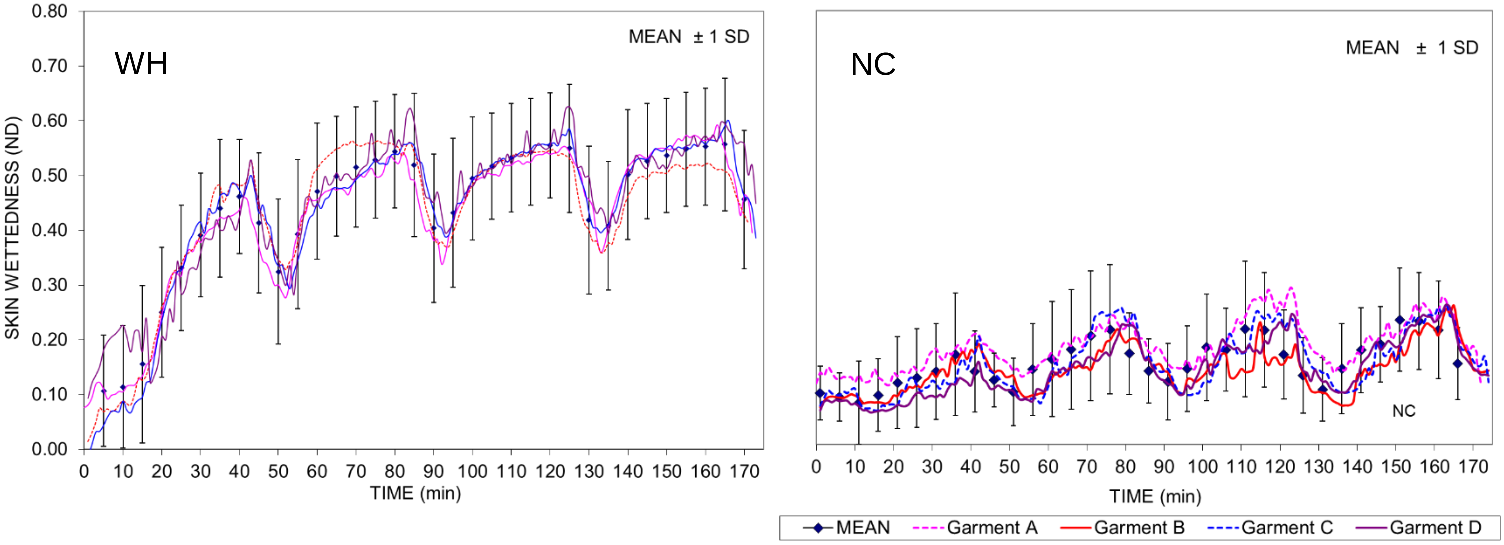
Note: Mean±1 SD values are for all garments and all volunteers.

Figure 5. Mean relative humidity under clothing ($\overline{RH}_{uc}$) in under warm-humid (WH = 27°C, 75% RH) and neutral (NC = 20°C, 50% RH) conditions



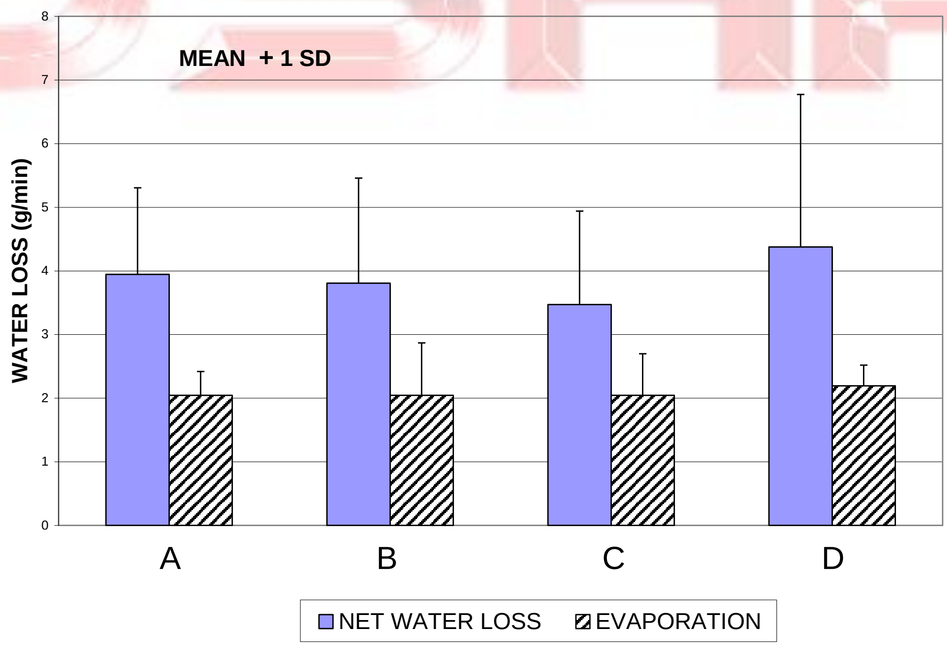
Note: Mean±1 SD values are for all garments and all volunteers.

Figure 6. Mean skin wettedness (ϖ) under warm-humid (Left: WH = 27°C, 75% RH) and neutral (Right: NC = 20°C, 50% RH) conditions



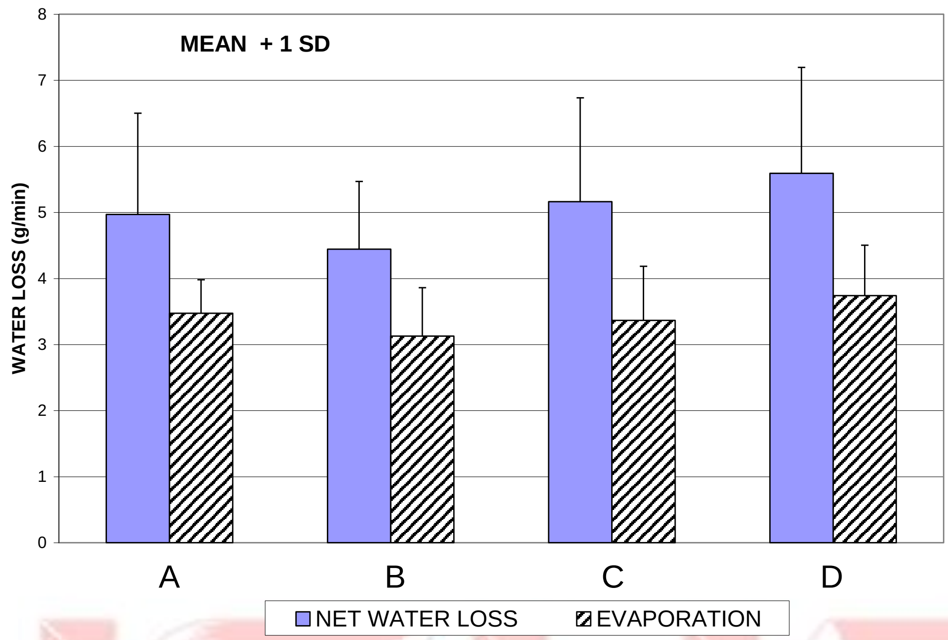
Note: Mean±1 SD values are for all garments and all volunteers.

Figure 7. Net water loss (R_w) and evaporation (R_{ev}) under neutral (NC = 20°C, 50% RH) conditions.



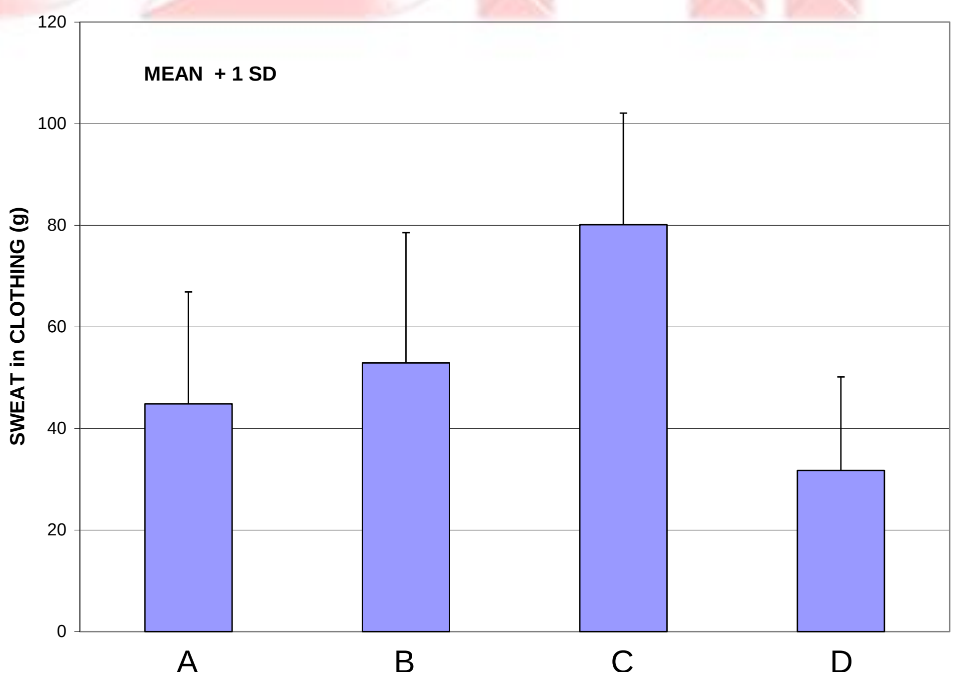
Note: Mean ±1 SD values are for all volunteers, and each of the 4 garments.

Figure 8. Net water loss (R_w) and evaporation (R_{ev}) under warm-humid (WH = 27°C, 75% RH) conditions.



Note: Mean ±1 SD values are for all volunteers, and each of the 4 garments.

Figure 9. Sweat retained in clothing (SW_{cl}) under warm-humid (WH=27°C, 75% RH) conditions.



Note: Mean ±1 SD values are for all volunteers, and each of the 4 garments.

ISSN: 2326-6333

Statistical Analysis – Physiological Data:

Statistical analysis was performed using a General Linear Model (GLM). When overall differences were significant ($\alpha \leq 0.05$), Tukey's Studentized Range Test (T-test) was used to determine which pairs were significantly different ($\alpha = 0.05$). The two environments were evaluated independently. Variables were T_{re}, ΔT_{re}, T_{sk}, ΔT_{sk}, T_b, RH, ω, (Table 3) rate of water loss (R_w), rate of evaporative loss (R_{ev}), percentage of sweating efficiency (%Eff), and sweat retention in clothing (SW_{cl}) (Table 4). Although there were a few overall significant differences for T_{re}, T_{sk}, T_b, RH_{uc} or ω, post hoc testing (T-test) indicated no significant differences between any two garments. Results for sweating, water loss and retention in clothing for the NC (20°C) environment were not significant.

For the NC condition, the effect of cycle (sequential change, cycle=rest+walk) for most variables was significant, but when there was an interaction of cycle and garment type, no overall conditions were found to be significant. In general, results for the WH condition were similar, but overall differences were found for the interaction of cycle and garment for the change in RH_{uc}, and $T_{sk.}$ The interaction for T_{sk} was obtained only after data smoothing was systematically conducted on the data, whereas all other results were obtained with and without similar data editing. The "cycle" analysis sequentially compared the mean value for each 40 min cycle. A significant interaction was also found between time and garment for T_b. The "time" analysis compared variable values for all four garments at the same point in time at 10 min intervals for the entire test session. For those variables where the overall differences were significant ($\alpha \leq 0.05$), Tukey's Studentized Range Test was used to determine which pairs were significantly different ($\alpha = 0.05$). For Sw_{cl}, there were significant differences between C and the other garments (C>A, B and D). For R_{ev}, only the difference between the B-D pair was significant (D>B).

DISCUSSSION

Manikin test results are very reproducible with very small variances [16]. Consequently results from thermal manikins are frequently statistically significant, but the actual differences are often quite small and have little real influence on subject responses. The results of the biophysical manikin testing found statistically significant differences for I_T between Uniform D and the other three Uniform (D > A,B,C), and Uniform C was greater than Uniform A. It has previously been suggested that a 10% difference in physical properties is required for a measurable difference on subject performance [17-18]. For the variables that included moisture, i_m and the i_m\clo, B,C > D, i_m and the combined i_m\clo variable, those results are near the 10% boundary. Measured I_T values fell well below the 10% threshold, and may be less likely to have elicited different physiological responses.

Based on those test results, in terms of physical properties, the four garments cannot be considered to be essentially equivalent (Table 2), but in terms of differences that resulted in physiological significant differences in response, the differences were primarily due to factors related to moisture. One can speculate that while sweat retained in clothing (SW_{cl}) may elevate skin moisture and impact comfort perception, only evaporative loss (R_{ev}) is thermophysiologically meaningful as only sweat that is evaporated alters heat exchange with the environment.

Although there were overall differences for T_{re}, T_b, and other variables, post hoc testing indicated no significant differences between any two garments for those variables. There were no significant differences between pairs of garments (T-test) observed for other physiological variables related to the subjects' overall or net thermal state. T_{re} and T_b are probably the best indicators of overall thermal status. The standard deviations (SD) range bars of the combined four garment means, and the relatively closeness of the mean values for each individual Uniform (A-D) for I_T (Figure 1) and T_b (Figure 3) indicate the large variability between volunteers, but very little difference between garments.

One goal of the study was to minimize the physiological response differences between the uniforms, so that the differences in the subjective comfort ratings between uniforms could be attributed primarily to clothing properties related to psychological comfort. One factor that makes these data different from other physiological clothing studies is that the combination of environmental stress (heat and humidity) and exercise are relatively benign, whereas most studies are designed to induce greater physiological strain. When developing physiological strain models, it is useful to be able to anchor the model to a more neutral or benign baseline. These results, and especially the NC results, provide those data.

In general, there were few significant differences in physiological response between garments, especially in the control (NC) environment. The few significant differences, as noted above, were related to water regulation. The differences in sweat loss and evaporation may reflect thermoregulatory responses that minimized changes in T_{re}. In addition, sweat that is not evaporated either increases skin wettedness or is retained in the clothing, factors which may contribute to surface friction and comfort sensations [9].

CONCLUSIONS

There are statistically significant differences between some of the tested uniforms in terms of insulation (I_T), water vapor permeability (i_m) and cooling power (i_m·clo). There were significant differences between Uniform A and C (C>A), D and all three other Uniforms (D>A, B, C) for I_T; and for i_m and i_m\clo between D and B or C (B, C>D). However, the actual value of the differences for I_T are small, and do not generally appear to have any significant physiological effects.

The use of body weight and water loss data was not particularly effective in discriminating between the different test uniforms. In the WH environment, for water retention Sw_{cl}, there were significant differences between the Uniform C and all three other Uniforms (C > A, B, D). For R_{ev}, only the difference between the B-D pair (D>B) was significant.

In terms of relating the physical properties of clothing to the physiological responses, the difference between B and D for R_{ev} (D>B) could be related to the significant differences in I_T, i_m and i_m·clo for the same pair of garments. The difference in I_T means was the greatest between these two garments (D=1.34 vs. B=1.30), and B is more permeable to water vapor (i_m), thus resulting in a small increase in potential for cooling (i_m·clo). Other significant differences in the physical properties between garments are not reflected by any difference in R_{ev}. For Sw_{cl} there is little correlation between statistically significant differences in the biophysical properties of the garments (C>A for I_T, C>D for i_m, i_m\clo) and physiological significant differences between garments.

ISSN: 2326-6333

DISCLAIMER

The views expressed in this paper are those of the authors and do not reflect the official policy of the Department of Army, Department of Defense, or the US Government. This research was supported in part by appointments to the Postgraduate Research Participation Program at the U.S. Army Research Institute of Environmental Medicine administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and USAMRDC.

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ISSN: 2326-6333