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Relationship between body heat content and finger temperature during cold exposure

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Brajkovic, Dragan, Michel B. Ducharme, and John Frim. Relationship between body heat content and finger temperature during cold exposure. *J Appl Physiol* 90: 2445–2452, 2001.—The purpose of the present experiment was to examine the relationship between rate of body heat storage (S), change in body heat content (ΔH_b), extremity temperatures, and finger dexterity. S, ΔH_b, finger skin temperature (T_{fing}), toe skin temperature, finger dexterity, and rectal temperature were measured during active torso heating while the subjects sat in a chair and were exposed to −25°C air. S and ΔH_b were measured using partitional calorimetry, rather than thermometry, which was used in the majority of previous studies. Eight men were exposed to four conditions in which the clothing covering the body or the level of torso heating was modified. After 3 h, T_{fing} was 34.9 ± 0.4, 31.2 ± 1.2, 18.3 ± 3.1, and 12.1 ± 0.5°C for the four conditions, whereas finger dexterity decreased by 0, 0, 26, and 39%, respectively. In contrast to some past studies, extremity comfort can be maintained, despite $\dot{S}$ that is slightly negative. This study also found a direct linear relationship between ΔH_b and T_{fing} and toe skin temperature at a negative ΔH_b. In addition, ΔH_b was a better indicator of the relative changes in extremity temperatures and finger dexterity over time than S.

finger dexterity; torso heating; heat storage; heat loss

COMPREHENSIVE REVIEWS ON THE EFFECTS of cold on manual performance have been carried out by Fox (16) and Provins and Clarke (34). They examined performance measures such as reaction time, tracking proficiency, tactile discrimination, muscle strength, and finger/hand dexterity. The present study examined the effects of cold on finger dexterity and the relationship between change in body heat content (ΔH_b), rate of body heat storage ($\dot{S}$), and finger skin temperature (T_{fing}).

Past studies have found that finger dexterity is decreased at $T_{fing} < 16°C$ (7, 17, 20). However, even if the hands are kept warm (i.e., hand skin temperature >28°C), finger dexterity decrements can still occur if the body (24, 28, 29) or forearms (26) are cooled. For example, decreasing mean body skin temperature (T_{sk}) below 25°C alone will decrease finger dexterity. In addition, actively heating the forearms [to a level just below the skin burn threshold of 45°C (31)] while a subject wore Arctic clothing and was exposed to −18°C air did not maintain finger comfort or dexterity (32). Hence, a warm forearm or hand will not necessarily prevent a decrease in finger dexterity during cold exposure.

Other factors used to explain the dexterity decrements observed in the cold include *1*) a decrease in nerve conduction velocity of the nerves in the arm, which would result in decreased finger tactile sensitivity (35, 44), *2*) an increase in finger synovial fluid viscosity (23), *3*) cooling of the small muscles of the hand (23), *4*) lack of sensory integration between the fingers (1, 37), *5*) the "distraction hypothesis" (the idea that the environment provides competing stimuli that interfere with responses elicited by the task-related stimuli) (41, 45), *6*) a decrease in finger blood flow (12), and *7*) a negative $\dot{S}$ [i.e., the rate of heat lost from the body is greater than the rate of heat generated (metabolic heat) and/or gained (by means of auxiliary heat) by the body] (36). $\dot{S}$ and ΔH_b are the focus of this study.

Numerous studies suggest that T_{fing} is strongly linked to the thermal state of the body. Most of these studies, however, did not actually measure $\dot{S}$ or ΔH_b but, rather, used differences in core temperature (8, 14, 38), ambient temperature (T_a) (15, 39), mean T_{sk} (17, 24, 28), mean body temperature (9), degree of active body heating (8, 15, 30), and clothing insulation (3) as an indicator of the differences in the thermal state of the body between any two conditions.

In examining the few studies that evaluated the relationship between $\dot{S}$ and extremity temperature, we find conflicting results. For example, Brajkovic et al. (4) reported recently that active torso heating can be used to indirectly warm bare hands during exposure to −15°C air. The idea of indirectly warming the hands by heating the body has been around since the early 20th century (27). The term indirect vasodilation is often used in the literature to describe the vasodilative response that occurs in one part of the body in response to heating another part of the body.

During the study of Brajkovic et al. (4), finger comfort [note: finger comfort may be defined as $T_{fing} > 23°C$, since Havenith et al. (21) found that the onset of pain can occur with a contact T_{sk} of 14–23°C] was

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maintained, despite $\dot{S}$ of −48 W. Wyndham and Wilson-Dickson (47) also found that finger comfort could be maintained, despite $\dot{S} < 0$ W.

In contrast, in a similar torso heating experiment, Goldman (18) found that extremity comfort could not be maintained despite $\dot{S}$ of 84 W.

Finally, Rapaport et al. (36) found that, in general, extremity comfort was maintained only at $\dot{S} \geq 0$ W. Unfortunately, none of the above-mentioned studies measured finger dexterity or examined the relationship between ΔH_b and T_{fing}.

The inconsistent findings between S and extremity temperature observed in the four studies mentioned above (4, 18, 36, 47) may be related to the methodology used to calculate $\dot{S}$. Three studies used thermometry to calculate $\dot{S}$, whereas Rapaport et al. (36) used partitional calorimetry (although the extremities and head were excluded in the calculation of $\dot{S}$). Partitional calorimetry may be more appropriately used in experiments that involve active heating of the body during cold air exposure (as in the 4 studies mentioned above), because the standard weighting coefficients used for rectal temperature (T_{re}) and T_{sk} during thermometry may be invalid during conditions in which there are large T_{sk} differences over the body. That is, during active heating in the cold, the temperature of heated regions of the body may be as high as 42°C, whereas the temperature of some of the unheated regions of the body (e.g., fingers) may be as low as 6°C (4). In support of the above explanation, Koscheyev et al. (25) recently found that changes in body heat content cannot be accurately calculated by thermometry when large T_{sk} differences exist over the body. Koscheyev et al. used a plastic tubing suit that allowed different parts of the body to be cooled or warmed with 7–45°C water.

In the present study, $\dot{S}$ and ΔH_b (calculated using whole body partitional calorimetry), extremity temperatures, and finger dexterity were measured during active torso heating in the cold (−25°C). It was hypothesized that the extremities would remain comfortable (i.e., $T_{fing} > 23$°C) only if $\dot{S}$ was ≥0 W. In addition, it was hypothesized that there is a direct linear relationship between T_{fing} and ΔH_b. Finally, it was hypothesized that ΔH_b may be a better indicator of extremity temperatures and finger dexterity over time than $\dot{S}$.

METHODS

Eight healthy, nonsmoking male volunteers with the following characteristics were recruited (mean ± SD): age 32.8 ± 7.4 yr, height 176.4 ± 6.3 cm, weight 82.4 ± 7.5 kg, and body surface area 1.99 ± 0.11 m^2. Body surface area was calculated using the formula of DuBois and DuBois (11). All subjects were medically screened by a physician at the Defence and Civil Institute of Environmental Medicine (DCIEM) before being asked for their written consent. This study was approved by the Human Ethics Committee at DCIEM.

The subjects were exposed to four randomly assigned conditions. Each cold exposure was initiated at ~10 AM each morning. *Condition 1*, HI(bare), involved torso heating with an electrically heated vest (EHV) while the subjects wore heavy insulation (HI: 3.6 clo, 0.556 m$^2 \cdot$°K$\cdot$W^{-1} Arctic clothing ensemble) and the hands were bare. *Condition 2*, LI(bare), was similar to *condition 1*, except the subjects wore lighter insulation (LI: 2.6 clo, 0.4 m$^2 \cdot$°K$\cdot$W^{-1}). *Condition 3*, HI(g + m), was similar to *condition 1*, except the subjects wore contact gloves and Arctic mitts during the test. *Condition 4*, HI(g + m)NP, was similar to *condition 3*, except the EHV was not powered during the test. The tests were done 1 wk apart from January to July. The extremity temperature responses observed during this study are representative of a mixed, male population in which some subjects may have had a greater degree of peripheral cold acclimatization as a result of spending more time working or playing outdoors during the winter. However, even in these so-called "acclimatized subjects," the extent of peripheral cold acclimatization that occurred (if any) was questionable. That is, human behavioral adaptations (i.e., wearing protective clothing, increasing one's level of activity, staying indoors during cold days) probably hindered or eliminated any cold acclimatization that might normally have taken place without such behavioral adaptations. Subjects sat in a chair while exposed to an ambient temperature of −25°C for 3 h during all tests, except when T_{fing} reached 6°C, at which point the exposure was terminated.

The subject wore the first two layers (designated LI or light insulation) or all three layers (designated HI or heavy insulation) of the Canadian Forces (CF) Arctic clothing ensemble during the cold exposure. The three-layer system included a fleece garment (first layer), an uninsulated inner parka and pants (second layer), and an insulated outer parka and pants (third layer). A thin pair of long, cotton underwear was worn under the fleece pants. Standard CF mukluks, woolen socks, and a balaclava were also worn. The 2.6- and 3.6-clo Arctic clothing insulation values do not take into account the long, cotton underwear worn under the fleece pants, which has a clo value of 0.3 (0.05 m$^2 \cdot$°K$\cdot$W^{-1}).

The EHV consisted of 10 Kapton insulated flexible heaters (Omega Engineering, Stamford, CT) fixed around the torso as follows: two (each 12 × 20 cm) on the chest, two on the abdomen (each 8 × 30 cm), one at each side of the torso (each 8 × 20 cm), two over the shoulder area (each 8 × 30 cm), and two on the back (each 15 × 30 cm). The heaters covered a total area of 0.266 m^2. The heaters were not in direct contact with the skin, but inside a fire-resistant pocket made of Nomex fabric. In addition, a 1-cm layer of Thinsulate insulation was placed inside the pocket on the outer surface of the heater. The Thinsulate insulation was covered by a piece of reflective Mylar to help reflect the radiative heat back to the torso. Once the heaters were placed inside the pockets, the pockets were sewn together to form a vest that covered a total area of 0.366 m^2.

A tight, short-sleeved Lycra body suit that extended down to the midthigh level was worn over the heaters to optimize the contact between the skin and the heaters.

Preselected voltages were sent by five current-limiting power supplies (2 model 6030A, 0–200 V/0–17 A, 1,000 W; 3 model 6034A, 0–60 V/0–10 A, 200 W; Hewlett-Packard) to the five pairs of heaters to achieve a T_{sk} of 42 ± 0.5°C under each heater. The power supplies were controlled by a computer that allowed the user to input the desired voltage for each pair of heaters in the EHV. To ensure that the T_{sk} under the heaters did not reach 45°C at any time, the computer turned off the heater completely if T_{sk} reached 44°C.

Physiological variables measured. During the 3-h cold exposure, the following physiological variables were measured: T_{fing} was measured using a cylinder-shaped thermistor [1.9 × 8.6 mm; Baxter 400 series rectal/esophageal probe without the protective sheath covering (time constant = 0.9 s in well-stirred water), Baxter Healthcare, Deerfield, IL]. A probe was placed on the pad of the "ring" fingertip of each hand. It was held in position on the skin with double-sided adhesive tape (3M Double-Stick Discs, 3M Medical Division, St. Paul, MN) without constricting the finger. Toe skin temperature (T_{toe}) was measured using a DCIEM laboratory-made, banjo probe (diameter = 10.2 mm, maximum height = 4.7 mm) that contains a protruding thermistor bead (model 44004, Yellow Springs Instrument, Yellow Springs, OH). The probe is similar in shape to the Yellow Springs Instrument standard surface probe (model 081), but it has a Plexiglas contact surface (instead of the stainless steel surface used in the Yellow Springs Instrument probe) and it has a time constant of 5 s in well-stirred water. A probe was placed on the lateral side of the big toe of each foot. The toe thermistor was held in place against the skin with surgical tape (3M Transpore Tape, 3M Canada, London, ON, Canada). T_{re} was measured by a thermistor (Pharmaseal 400 series, Baxter, Valencia, CA) inserted 15 cm beyond the anal sphincter. T_{fing}, T_{toe}, and T_{re} were measured five times per minute over the course of 3 h using a data acquisition system (model 3497A data acquisition/control unit, Hewlett-Packard). An average value was printed out each minute.

Gas exchange analyses. Open-circuit spirometry was used to determine O_2 uptake ($\dot{V}o_2$, l/min STPD) and CO_2 output (l/min STPD) every minute for the 3-h cold exposure, except at 0–5, 30–35, 60–65, 90–95, 120–125, and 150–155 min. The metabolic mouthpiece was removed during these times so that the subjects could perform the finger dexterity tests without any arm movement or visual field restrictions. Removing the mouthpiece for 5 min every 25 min also allowed the subjects to take a break from having the mouthpiece in for so long. After ~5 min, the mouthpiece was placed in the mouth again, but the metabolic rate did not stabilize for ~3–5 min. Therefore, in the presentation of S and ΔH_b, 10-min periods of data are missing, because the metabolic data were not collected or they were unstable immediately after the mouthpiece was inserted. The subjects used a mouthpiece equipped with a T-shaped valve (series 7920, Hans Rudolph, Kansas City, MO) that directed expired gases by means of a 3-m piece of plastic tubing into a 5-liter mixing box located outside the cold chamber. An aliquot of dried expired gases was pumped to O_2 and CO_2 analyzers (models S-3A and CD-3A, respectively, Ametek Instruments, Paoli, PA). $\dot{V}o_2$, CO_2 output, and respiratory exchange ratio (RER) were calculated and printed out every minute. The portion of the plastic tubing that was inside the cold chamber was wrapped with electrical heating tape to prevent any ice buildup inside the hose. A temperature controller was used to maintain the tape at 43°C. The heating tape was then wrapped with pipe-insulating foam that had 2-cm-thick walls.

Heat balance calculation. S was calculated as shown; all variables are measured in watts

$$S = M - \dot{W} - (\dot{R} + C + K) - \dot{E}_{sk} - \dot{E}_{resp} - \dot{C}_{resp}$$

where M is metabolic rate, W is rate of work, $\dot{R} + C + K$ represents radiative, convective, and conductive heat flows, E_{sk} is evaporative heat loss from the skin, and E_{respir} is evaporative respiratory heat loss.

ΔH_b (in kJ), i.e., the change in body heat content at *time t* [in min, $H_{b(t)}$] from the initial change in body heat content at 12 min [$H_{b(12)}$], was also calculated as follows

$$\Delta H_b = H_{b(t)} - H_{b(12)}$$

M was measured by using the following formula: M = 352(0.23·RER + 0.77)$\dot{V}o_2$ (33), where $\dot{V}o_2$ is expressed in l/min STPD. $\dot{W}$ was equal to zero, since subjects sat in a chair for the entire 3-h cold exposure. $\dot{R} + C + \dot{K}$ was measured using heat flux transducers (HFTs) with embedded thermistors [model HA13-18-10-P(C), Concept Engineering, Old Saybrook, CT]. The mean body heat flux (in W/m^2) for each subject was multiplied by the surface area of the subject (in m^2) to determine the mean body heat flow ($\bar{H}_b$, in W). The HFTs were recalibrated, and the values were corrected for the decreased heat flux measurement that occurs because of the thermal resistance of the HFTs (13).

The HFTs were placed on the body, as described by Brajkovic et al. (4), using a modified version of the thermistor sites used by Hardy and DuBois (19). Ten HFTs were used to represent the heat flux of the heated portion of the body, and 10 HFTs were used to represent the unheated regions of the body. The heat flux and T_{sk} weighting coefficients for the torso region originally used in the system of Hardy and DuBois were modified to represent the heated and unheated areas of the torso. The "heated region of torso coefficient" ($Coeff_{heated}$) for each subject was calculated by dividing the vest area (0.266 m^2) by the entire body surface area (in m^2). Once $Coeff_{heated}$ was calculated, the front and back "unheated region of torso coefficients" ($Coeff_{unheated}$) for each subject was calculated as follows: $Coeff_{unheated} = (0.35 - Coeff_{heated})/2$, where 0.35 is the coefficient of Hardy and DuBois used to represent the torso area.

E_{respir} was calculated using the following formula: $E_{respir} = \rho \cdot \lambda \cdot V_E(W_{respir} - W_a)$ (6), where ρ represents the density of air (STPD) = 0.001293 kg/l, λ represents the latent heat of vaporization = 675 W·h·kg^{-1}, V_E represents the expired air volume in l/h STPD, W_{respir} represents the humidity ratio of respired air (kg water/kg dry air), and W_a represents the humidity ratio of ambient air (kg water/kg dry air). $W_{respir} - W_a = 0.622[P_{respir} - (101.325 - P_{respir}) - P_a \div (101.325 - P_a)]$, where P_{respir} (in kPa) represents the saturated vapor pressure of the expired air = 100% saturated at 29.6°C = 4.14 kPa (5) and P_a (in kPa) represents the vapor pressure of the ambient air = 100% saturated at −25°C = 0.08 kPa. Convective respiratory heat loss ($\dot{C}_{respir}$) was calculated using the following formula: $C_{respir} = \rho \cdot \dot{V}_E(T_{respir} + T_a)(c_{pa} + c_{pwv} \cdot W_a)$ (6), where V_E represents the expired air volume (in l/h STPD), T_{respir} represents the expired air temperature = 29.6°C (6), T_a represents the ambient temperature = −25°C, c_{pa} represents the specific heat of dry air = 0.28 W·h·kg^{-1}·°C^{-1}, c_{pwv} represents the specific heat of water vapor = 0.52 W·h·kg^{-1}·°C^{-1}, and W_a represents the humidity ratio of ambient air (kg water/kg dry air) = $0.622[P_a/(101.325 - P_a)]$, where P_a (in kPa) represents the vapor pressure of ambient air = 100% saturated at −25°C = 0.08 kPa. $\dot{E}_{sk}$ was estimated from a model developed by Cain and McLellan (5). The model used vapor pressure readings obtained with six humidity sensors that were positioned ~5 and 15 mm above the skin surface [i.e., each sensor was inside a plastic housing that was placed on the skin (sensor 5 mm from skin surface) and on the first layer of clothing (sensor 15 mm from skin surface)] at three different locations on the body. A temperature thermistor was attached to each humidity sensor. Two humidity sensors were placed on the lateral side of the right calf, two on the anterior side of the left thigh, and two on the lateral side of the right upper arm. The water vapor pressure at the skin was predicted from the water vapor measurements provided by the sensors in the clothing. This was, in turn, used in calculating E_{sk}. The model was viewed as one-dimensional flow of water vapor through the multiple layers of Arctic clothing, which produced resistance to the flow.

Finger dexterity tests. During the 3-h cold exposure, the subjects were asked to perform a C-7 rifle disassembly and assembly task (C-7 rifle task) or a Purdue pegboard test (PP test) every 30 min. The C-7 rifle task was done at 0, 60, 120, and 180 min; the PP test was done at 30, 90, and 150 min. The C-7 rifle task was chosen because it was representative of the type of finger dexterity task that might be carried out by soldiers in the field. It was used as a measurement of gross finger dexterity. Subjects were required to do a "detailed stripping" of the rifle as outlined in *The Warrior* CF combat survival manual (10). This involves an eight-step "field strip" (*step 9* was omitted for this experiment) and a six-step "detailed strip" (*step 3* was omitted for this experiment). A total of 10 pieces (primarily made from metal) were disassembled. The process was then repeated in the reverse order to reassemble the C-7 rifle. The quantitative measure used to assess gross finger dexterity was the total time (in seconds) required to disassemble and assemble the rifle. The PP test, on the other hand, is an extensively used fine finger dexterity test, which has been shown to be a reliable and valid measure of finger dexterity (2, 42). The Purdue pegboard consists of a pegboard with two columns of small holes down the middle of the board and four small cups along the top of the board that contain small metal pins, washers, and collars. The object of the PP test is to assemble as many units as possible in a 1-min period (one assembled unit consists of pin, washer, collar, and washer). One point was awarded for each piece (i.e., pin, washer, or collar) placed on the PP board. The subjects were asked to perform three trials of the 1-min test with a 15- to 30-s break between each trial. A PP score was recorded for each trial and an average of the three PP scores is presented. During HI(bare) and LI(bare), the tests were done with bare hands; during HI(g + m) and HI(g + m)NP, the Arctic mitts were removed, but the knitted, contact gloves were kept on for the duration of the dexterity tests. During the completion of the three PP test trials, the hands were exposed to the −25°C air for ~4 min, whereas the C-7 rifle task took ~1–2 min to complete.

The subjects were taught how to do the C-7 test and the PP test by the investigators during a 45-min training session that was arranged with the subject before the experimental sessions were started. In addition to the training session, during the experimental sessions, the subjects were asked to practice the C-7 and PP tests before each entry into the cold chamber. The subjects practiced the tests until a plateau in performance was observed. The subjects practiced the tests outside the cold chamber while wearing the same CF Arctic clothing worn inside the cold chamber (excluding the uninsulated and insulated ski pants), but they were exposed to a 25°C ambient environment.

Statistical analyses. A two-way ANOVA for repeated measures was used to compare HI(bare) and LI(bare) (*comparison 1*), HI(bare) and HI(g + m) (*comparison 2*), and HI(g + m) and HI(g + m)NP (*comparison 3*). The independent variables were clothing insulation and time, hand insulation and time, and heating level and time for *comparisons 1, 2,* and *3*, respectively. These analyses were done for the dependent variables C-7 rifle time, PP test score, T_{fing}, T_{toe}, T_{re}, ΔH_b, and $\dot{S}$ from 0 to 180 min. Five-minute averages were calculated for the 180 min of data, so that 2, 7, and 12 min represented the data from 0 to 4 min, 5 to 9 min, and 10 to 14 min. Five-minute averages were not calculated for the finger dexterity data (i.e., C-7 rifle time and PP test score), because data for these variables were collected every 30–60 min. Results were considered statistically significant at $P \leq 0.05$ (using the Greenhouse-Geisser adjustment for repeated measures). A Newman-Keuls post hoc test was used to determine whether there was a significant difference in any of the dependent variables from 2 to 177 min. Values are means ± SE.

RESULTS

Extremity temperatures and T_{re} at the start of the tests averaged 33.0 ± 0.4 and 37.25 ± 0.07°C, respectively, with no difference between conditions. These temperatures indicate that the subjects were in a state of thermoneutrality at the start of the cold exposure. During HI(g + m), HI(bare), and LI(bare), $\dot{S}$ remained stable at 13 ± 5 W, −11 ± 5 W (not significantly different from 0 W), and −46 ± 8 W, respectively (Fig. 1), over the course of 3 h, whereas ΔH_b values during the three conditions were 140 ± 41, −125 ± 36, and −407 ± 70 kJ, respectively, after 3 h (Fig. 1). These changes in ΔH_b were significant ($P \leq 0.05$) relative to the ΔH_b values at 12 min. At the end of the 3-h exposure, T_{fing} was 34.9 ± 0.4, 31.2 ± 1.2, and 18.3 ± 3.1°C, and T_{toe} was 33.2 ± 0.8, 28.2 ± 1.8, and 16.2 ± 2.1°C (Fig. 1). The decrease in T_{fing} was not significant ($P > 0.05$) relative to that at 2 min during HI(g + m) and HI(bare), but it was significant during LI(bare).

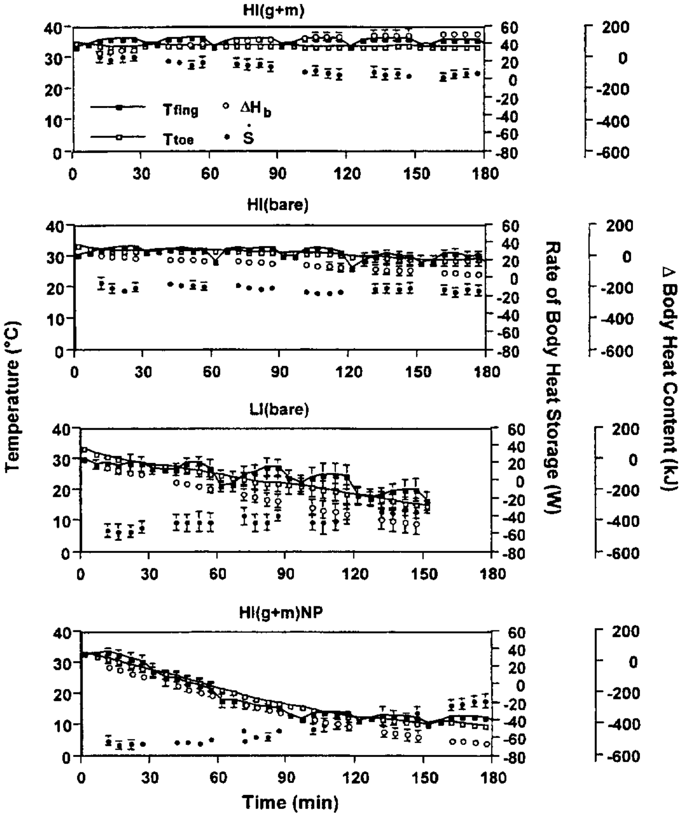

Fig. 1. Relationship between extremity temperature, rate of body heat storage, and change in body heat content for all conditions during exposure to −25°C air. HI(bare) involved torso heating with an electrically heated vest while subjects wore heavy insulation and hands were bare; LI(bare) was similar to HI(bare), except subjects wore lighter insulation; HI(g + m) was similar to HI(bare), except subjects wore contact gloves and Arctic mitts; HI(g + m)NP was similar to HI(g + M), except electrically heated vest was not powered. Values are means ± SE; $n = 8$, except LI(bare), where $n = 6$.

The decrease in T_{toe} was not significant ($P > 0.05$) relative to that at 2 min during HI(g + m), but it was significant during HI(bare) and LI(bare).

During HI(g + m), T_{re} increased significantly ($P \leq 0.05$) by 0.23 ±0.04°C during the 1st h of cold exposure and then gradually decreased to its original value (observed at 2 min) at 177 min (Fig. 2). During HI(bare), there was no significant ($P > 0.05$) change in T_{re} from 2 to 167 min and then a significant decrease (0.1°C) during the last 13 min of the exposure (relative to the value observed at 2 min; Fig. 2), whereas during LI(bare), T_{re} followed the same T_{re} response observed during HI(bare) for the first 154 min, after which no data were available for LI(bare) (Fig. 2). During LI(bare), four subjects were removed from the cold chamber at 70, 141, 154, and 178 min, respectively, because T_{fing} reached 6°C in each case.

During HI(g + m)NP, $\dot{S}$ increased significantly ($P \leq 0.05$) from -65 ± 5 to -19 ± 7 W from 12 to 177 min (Fig. 1) because of an increase in shivering. During this same time period, T_{fing} decreased significantly from 32.4 ± 0.4 to 12.1 ± 0.5°C (Fig. 1), T_{toe} decreased significantly from 32.4 ± 1.1 to 9.1 ± 0.2°C (Fig. 1), and T_{re} decreased significantly by 0.57 ± 0.08°C by 177 min (Fig. 2). However, the extremity response during HI(g + m)NP did follow the ΔH_b response over time (i.e., ΔH_b decreased exponentially over time as did T_{fing} and T_{toe}; Fig. 1). During HI(g + m)NP, the lowest extremity temperatures (T_{fing} and T_{toe} = 12.1 ± 0.5 and 9.1 ± 0.2°C, respectively) were observed when ΔH_b was considerably negative (i.e., -533 ± 42 kJ at 177 min) relative to the ΔH_b values observed in the other conditions.

During the 3-h exposure, finger dexterity was maintained during HI(bare) and HI(g + m), but it decreased significantly ($P \leq 0.05$) during LI(bare) and HI(g + m)NP. During LI(bare), C-7 rifle time increased significantly from 82 ± 9 to 102 ± 12 (24% increase) from 0 to 120 min (Table 1) and PP test score decreased significantly from 43 ± 4 to 31 ± 4 points (28% decrease) from 30 to 150 min (Table 2), whereas during HI(g + m)NP, C-7 rifle time increased significantly from 104 ± 6 to 144 ± 19 s (39% increase) from 0 to 180 min (Table 1) and PP test score decreased significantly from 18 ± 3 to 11 ± 1 points (39% decrease) from 30 to 150 min (Table 2). Finger dexterity decreased on average for the two dexterity tests by 0, 0, 26, and 39% for HI(g + m), HI(bare), LI(bare), and HI(g + m)NP, respectively. During LI(bare) and HI(g + m)NP, the decrements in finger dexterity occurred at $T_{fing} < 16$°C. This observation is in agreement with the findings of other studies (7, 17, 20).

Examination of the plot of mean T_{fing} and ΔH_b values for all eight subjects [or 6 subjects in the case of LI(bare)] for 3 h in all four conditions (Fig. 3) shows a direct linear relationship between T_{fing} and ΔH_b (i.e., T_{fing} decreased when ΔH_b decreased) at $\Delta H_b < 0$ kJ; however, there was no change in T_{fing} at $\Delta H_b \geq 0$ kJ. The same linear relationship was observed between T_{toe} and ΔH_b (Fig. 4), although there was less scatter in the data, probably because the toes were enclosed in boots and were not used to perform the dexterity tests.

Table 1. *C-7 rifle time (seconds) for all conditions during exposure to −25°C air*

Time, min	Condition HI (bare)	LI (bare)	HI (g + m)	HI (g + m)NP
0	92 ± 5.7	82 ± 8.5	97 ± 5.7	104 ± 6.0
60	84 ± 5.9	90 ± 8.4	89 ± 3.5	101 ± 8.0
120	88 ± 6.7	102 ± 11.8	92 ± 4.5	131 ± 15.4
180	86 ± 6.6		93 ± 7.0	144 ± 18.7

Values are means ± SE; n = 8, except for LI (bare), where n = 6. HI (bare) involved torso heating with an electrically heated vest while subjects wore heavy insulation and hands were bare; LI (bare) was similar to HI (bare), except subjects wore lighter insulation; HI (g + m) was similar to HI (bare), except subjects wore contact gloves and Arctic mitts; HI (g + m)NP was similar to HI (g + m), except electrically heated vest was not powered. There were no significant differences between HI (bare) and LI (bare) and between HI (bare) and HI (g + m). There was a significant difference at 120 and 180 min between HI (g + m) and HI (g + m)NP.

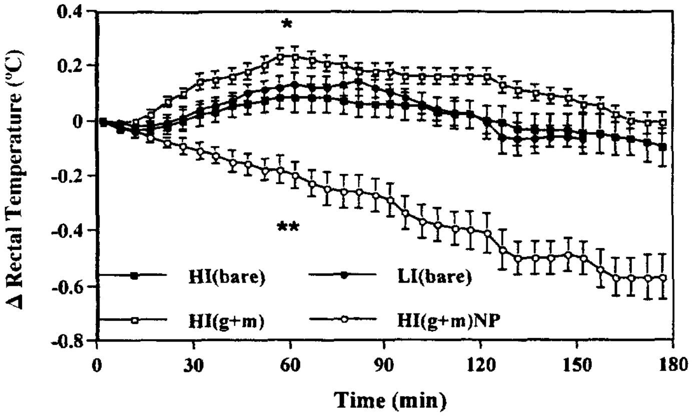

Fig 2. Change in rectal temperature (T_{re}) for all conditions during exposure to −25°C air. Values are means ± SE; n = 8, except for LI(bare), where n = 6. *Significant difference in T_{re} during HI(g + M) from 0 min; **significant difference in T_{re} during HI(g + m)NP from 0 min.

DISCUSSION

It was hypothesized that the extremities would remain comfortable (i.e., $T_{fing} > 23$°C) only at $\dot{S}$ (calcu-

Table 2. *Purdue pegboard score (points) for all conditions during exposure to −25°C air*

Time, min	Condition HI (bare)	LI (bare)	HI (g + m)	HI (g + m)NP
30	46 ± 3.3	43 ± 4.3	18 ± 2.5	18 ± 2.6
90	49 ± 3.6	40 ± 4.9	19 ± 2.5	14 ± 1.6
150	48 ± 3.9	31 ± 4.4	21 ± 2.1	11 ± 0.9

Values are means ± SE; n = 8, except for LI (bare), where n = 6. See Table 1 for explanation of conditions There was a significant difference at 90 and 150 min between HI (bare) and LI (bare), at 30, 90, and 150 min between HI (bare) and HI (g + m), and at 90 and 150 min between HI (g + m) and HI (g + m)NP.

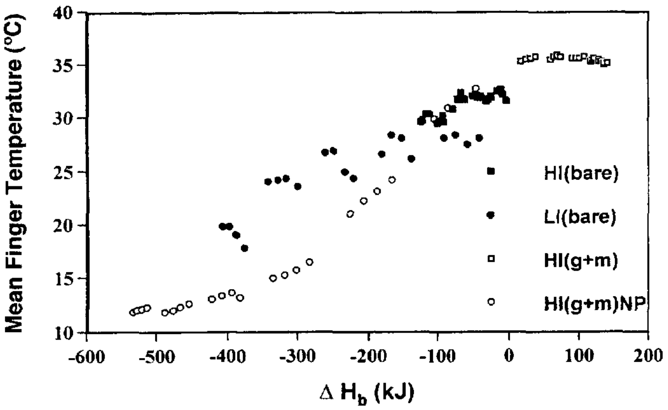

Fig. 3. Relationship between mean finger temperature and change in body heat content (ΔH_b) for all conditions. Values are means ± SE; $n = 8$, except for LI(bare), where $n = 6$.

lated using whole body partitional calorimetry) ≥ 0 W. This null hypothesis was rejected; this study found that extremities remained comfortable for a considerable length of time (i.e., 1–2 h), even when $\dot{S}$ was slightly negative. In addition, it was hypothesized that there is a direct relationship between T_{fing} and ΔH_b. This hypothesis was accepted for $\Delta H_b \leq 0$ kJ. Finally, it was hypothesized that ΔH_b was a better indicator of the extremity temperatures and finger dexterity over time than $\dot{S}$. This hypothesis was accepted on the basis of an examination of the data for the full 3-h cold exposure.

Relationship between $\dot{S}$, ΔH_b, and T_{fing}. In relation to the association between $\dot{S}$ and T_{fing}, the present study found that the extremities remained comfortable over the course of 3 h at $\dot{S} \geq 0$ W. These results support the general conclusion of Rapaport et al. (36) that extremity comfort is maintained at $\dot{S} \geq 0$ W, but only if the relationship between $\dot{S}$ and extremity comfort is examined over the entire 3-h cold exposure. That is, the subjects in the study of Rapaport et al. were normally subjected to cold exposures of ~1 h, instead of 3 h. The conclusions drawn about the relationship between $\dot{S}$ and T_{fing} should take into account the duration of the cold exposure at $\dot{S} < 0$ W. For example, in the present study, we found that the extremity comfort (i.e., $T_{fing} >$ 23°C) could be maintained for 2 h when $\dot{S}$ was -46 ± 8 W [see T_{fing} during LI(bare) in Fig. 1] and for 1 h when $\dot{S}$ was -65 ± 5 W [see T_{fing} during HI(g + m)NP in Fig. 1]. Hence, in the present study, if one were only to examine the relationship between S and T_{fing} during the 1st h of cold exposure, the findings would contradict those of Rapaport et al. that extremity comfort is maintained only at $\dot{S} \geq 0$ W. That is, we found that finger comfort could be maintained during the 1st h of cold exposure even at $\dot{S} < 0$ W. The contrasting conclusions may be attributed to the fact that Rapaport et al. did not include the head, hands, or feet in their partitional calorimetry calculation of $\dot{S}$, whereas in the present study the entire body was included in the calculation.

The present results do agree with the findings of Brajkovic et al. (4) and Wyndham and Wilson-Dickson (47): in both studies it was reported that a comfortable extremity temperature can be associated for a limited time with $\dot{S} < 0$. However, these studies used thermometry; hence, the actual heat debt may have been less than the calculated heat debt, since it has been shown that thermometry-based calculations of S are not accurate when large T_{sk} differences exist over the body (25). In addition, Vallerand et al. (43) found that thermometry-based calculations of $\dot{S}$ can significantly overestimate partitional calorimetry-based calculations of S by as much as 100%.

The present findings also suggest that $\dot{S}$ may have been overestimated in Goldman's (18) experiment, which involved active torso heating during exposure to −40°C air. Goldman found that extremity comfort could not be maintained, despite S (calculated by thermometry) of 84 W. One possible explanation for Goldman's finding is that the weighting coefficients (T_{re} and $\dot{S}$ of 0.67 and 0.33, respectively) he used were inappropriate, because they are normally used in conditions where subjects are exposed to a cold stress. In Goldman's experiment, subjects were exposed to a very cold ambient environment (−40°C), but they were also very well insulated (4.3 clo Arctic garment and mitts) and actively heated (48–49°C hot air directed at torso). Therefore, Goldman's subjects were most likely not under a considerable cold stress. A different set of coefficients may have decreased the $\dot{S}$ reported by Goldman and, hence, may explain why his subjects cooled, despite $\dot{S}$ of 84 W.

This study introduced a calculation of ΔH_b, whereas past calorimetry and thermometry studies that examined the relationship between T_{fing} and the thermal state of the body (4, 18, 36, 47) calculated as S, instead of ΔH_b. The present study found a direct linear relationship between T_{fing} and ΔH_b at $\Delta H_b < 0$ kJ but no change in T_{fing} at $\Delta H_b \geq 0$ kJ (Fig. 3). The same type of relationship was observed between T_{toe} and ΔH_b (Fig. 4). To the authors' knowledge, these relationships have not been reported in any past studies.

This study also found that ΔH_b was a better indicator of the change in extremity temperatures over time

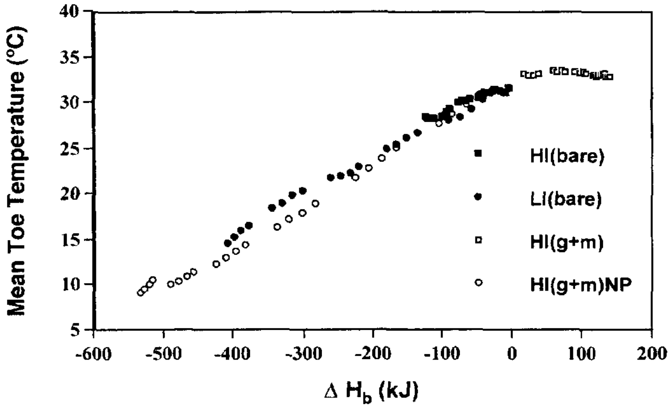

Fig. 4. Relationship between mean toe temperature and ΔH_b for all conditions. Values are means ± SE; $n = 8$, except for LI(bare), where $n = 6$

than $\dot{S}$. Evidence for this is provided by examining the extremity temperatures, ΔH_b, and $\dot{S}$ in Fig. 1 for LI(bare) and HI(g + m)NP. During LI(bare), for example, S remained stable at -46 ± 8 W during the entire cold exposure, whereas T_{fing} and T_{toe} decreased to 18.3 ± 3.1 and 16.2 ± 2.1°C, respectively. In contrast, ΔH_b decreased at a rate similar to the temperature of the extremities. In addition, during HI(g + m)NP, $\dot{S}$ increased from -65 ± 5 to -19 ± 7 W, whereas T_{fing} and T_{toe} decreased to 12.1 ± 0.5 and 9.1 ± 0.2°C, respectively. In contrast, ΔH_b decreased at a rate similar to the temperature of the extremities.

The present study also found that T_{fing} was maintained at a comfortable level [$T_{fing} > 23$°C (21)] and that finger dexterity was maintained even at $\Delta H_b < 0$ kJ (i.e., -125 ± 36 kJ), but T_{fing} and finger dexterity were decreased when there was a greater heat debt (i.e., -407 ± 70 kJ). In the present study, the ΔH_b at which T_{fing} decreased below 23°C was, on average, -250 kJ (on the basis of the best linear fit of the T_{fing} data at $\Delta H_b \leq 0$ kJ); above this value, the fingers were generally comfortable.

Relationship between T_{re} and extremity temperature during active torso heating. Veghte (46) found that, during exposure to -17°C air, bare extremities cooled very rapidly (within 8 min), despite a normal core temperature of 37.2–37.3°C (maintained by providing >10 clo of body clothing insulation). Veghte's study suggests that the local cold stress imposed on the hands is more important than the thermal state of the body in determining finger comfort. However, for a similar core temperature, the present study found that bare hands can remain comfortable for 3 h, even when they are exposed to a very cold (-25°C air) local cold stress [see HI(bare) in Figs. 1 and 3]. The key difference is that in the present study the extremities were kept warm during HI(g + m), HI(bare), and most of LI(bare), because the active heating on the torso triggered a vasodilative response in the extremities that was large enough to keep the hands and feet warm, which, in turn, prevented an increase in core temperature. In contrast, during Veghte's study, there was no active torso heating, and therefore there was no need for the body to dissipate any excess heat to the extremities. Hence, a comparison of Veghte's study with the present work shows the importance of the thermal state of the body (i.e., H_b and $\dot{S}$) on extremity comfort. Although T_{re} was similar between the studies, H_b and $\dot{S}$ were most likely lower during Veghte's study. Therefore, this comparison shows that core temperature alone cannot adequately predict T_{fing}.

Overall, this study found that ΔH_b was a good indicator of extremity temperature response over time during all conditions, whereas T_{re} and $\dot{S}$ were good indicators of extremity temperature in only some conditions.

Effect of wearing gloves on finger dexterity. In an experiment in which they examined the effect of 14 types of thin gloves (1–2 mm thick) on finger dexterity, Havenith and Vrijkotte (22) found a decrease in finger dexterity of up to 70% when gloves were worn compared with bare-hand performance. In the present study, the thin gloves worn during torso heating decreased finger dexterity by 60% compared with bare-hand performance [cf. PP test scores for HI(g + m) with those for HI(bare)].

In contrast, during the C-7 rifle task, a significantly higher rifle task time was not observed during the 3-h cold exposure when bare-hand performance was compared with gloved-hand performance. The lack of increase in C-7 rifle task time when bare-hand performance was compared with gloved-hand performance may be because the C-7 rifle task is a gross finger dexterity test, not a fine finger dexterity test; therefore, the C-7 task may not have been sensitive enough to discriminate between the fine finger dexterity differences that existed over time. Stang and Wiener (40) also found that grosser hand movements were less affected than finer hand movements during work in the cold.

The lack of a difference in C-7 rifle performance over the course of 3 h may have occurred because the duration of the C-7 rifle task may not have been long enough (the C-7 task takes ~1–2 min to complete when the fingers are comfortable) to show any decrement in finger dexterity that might have existed if the C-7 task was longer (e.g., ≥5 min).

Relationship between finger dexterity and ΔH_b. In the present study, for a given level of hand insulation, finger dexterity decreased significantly over time when there was a decrease in H_b (Fig. 3, Table 2).

The results of this study are in agreement with past studies which found that finger dexterity decrements generally occur at $T_{fing} < 16$°C (7, 17, 20) (Fig. 1, Table 2). In the present study, T_{fing} of 15°C corresponded to ΔH_b of -440 kJ (on the basis of the best linear fit of the T_{fing} data at $\Delta H_b \leq 0$ kJ; Fig. 3). Daanen (9) also examined the relationship between finger dexterity and body cooling. He did not measure ΔH_b, but he did find a strong ($r = 0.82$–0.90) linear relationship between mean body temperature and finger dexterity, which supports our finding.

Conclusion. Torso heating can be used to keep an individual's bare hands and insulated feet warm (T_{fing} and $T_{toe} \geq 28$°C) during exposure to -25°C air at rest for 3 h when Arctic clothing is worn. Extremity temperatures were comfortable (i.e., >23°C) for the entire 3-h cold exposure only in conditions when $\dot{S}$ was ≥ 0 W, but for shorter-duration cold exposures (e.g., 1–2 h) comfortable extremity temperatures could be maintained, despite $\dot{S}$ slightly below 0 W. Overall, it is important to consider the duration of an experiment when conclusions are made regarding the relationship between $\dot{S}$ and extremity temperatures. ΔH_b over time was a better indicator of the relative changes in extremity temperatures and finger dexterity over time than $\dot{S}$.

Overall, there was a direct linear relationship between T_{fing} and ΔH_b at $\Delta H_b < 0$ kJ; however, there was no change in T_{fing} at $\Delta H_b \geq 0$ kJ. The same relationship was observed between T_{toe} and ΔH_b.

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