Final Report

Performance Evaluations of Micro-Climate Cooling Products

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BACKGROUND AND SIGNIFICANCE

A number of occupations require routine exposures to extreme temperature conditions, such as fire fighters; hazardous materials handlers; forestry, agricultural, construction, and military personnel; and others. Persons performing job tasks in these extreme environments are at risk for the development of heat related injuries and illnesses. Additionally, a number of athletic training camps are positioned in extreme temperature and humidity conditions, and the increase in the number of heat related incidents have prompted concerns.

Micro-climate cooling products, such as commercially available gel or water based vests, have been developed to reduce the risk of heat stress and heat related injuries and illnesses by reducing core body temperature and heart rate either during or following work in hot environments (Bennett et al, 1995; Chen et al, 1997). However, no national standards or minimum performance standards currently exist for commercially micro-climate cooling products. Additionally, testing performed on these types of devices has been task specific (primarily military operation specific), making generalization of findings to industrial occupations or recreational activities difficult.

The objectives of this study were to evaluate cooling effectiveness of three such micro-climate cooling products during exercise protocols; more specifically to: (1) determine cooling capacity performance of selected commercially available micro-climate cooling vests using thermal manikins (TMs), (2) evaluate recovery rates associated with ClimaTech Safety cooling vests following heat exposure while performing light exercise, and (3) provide performance assessment data using human subjects (quantitative physiological response assessments and qualitative comfort and usability assessments) while performing light exercise. The TMs provided a no risk method (no human subjects) for assessing product performance that can be easily replicated. However, human performance testing is needed to obtain crucial information on (a) the effects of wearing the products, as the TMs do not respond as a human would to the same stress, and (b) on the ability of persons to use the device without interfering with job task performance or introducing other risks (such as musculoskeletal discomfort/disorders). The project was completed in three phases, each phase associated with each objective.

METHODOLOGY

Phase 1: Cooling Capacity Assessment of ClimaTech Safety Cooling Vests using Thermal Manikins

Two ClimaTech Safety micro-climate cooling vests and a competitor product were tested to determine the cooling capacity under controlled conditions using Thermal Manikins (TMs) at the Natick Soldier Center, Natick, MA. The vests tested included ClimaTech Safety's HeatShield (gel vest) and AirVest (continuous compressed air supply), and Bullard's IsoTherm (ice pack vest). TMs are a ten-zone, heated aluminum manikin designed as the 50^{th} percentile male and are available for use by the US Army Natik Soldier Center (a division of the National Protection Center) for testing of personal protective equipment.

For each vest, two trials were performed to assess the reliability of the vest under extreme conditions. The ambient environmental conditions were set to a temperature of 35^{o}C (95^{o}F), 40% relative humidity, and 0.9 $m \cdot sec^{-1}$ (2 mph) wind speed. The TM was provided with electrical current until reaching an equilibrium temperature, then fitted with the appropriate vest. A Joint Lightweight Integrated Suit Technology (JSLIST) MOPP IV overgarment was then fitted over the TM. The power required to maintain the TM equilibrium temperature was recorded at 1-minute intervals over one complete exhaustive cycle of the HeatShield and IsoTherm, and for one hour for the AirVest (as cooling time is continuous).

Cooling capacity (measured in watts) was calculated as the power input to the TM and averaged over the first hour. Cooling capacity is calculated by multiplying the cooling rate by the cooling duration. The cooling rate and duration of cooling was recorded and compared to previous data obtained on other vests tested under identical conditions (Masadi et al, 1991). Cooling measures were limited to those in which over 100 watts of cooling were provided by the vests. Previous research has shown that cooling capacities less than this value are not effective at reducing core body temperatures, though persons may report sensations of cooling.

Phase II: Recovery Rates Associated with ClimaTech Safety Cooling Vests

Participants

Eight healthy fit male participants were recruited from the Virginia Tech population through advertisements placed throughout campus. Potential participants were provided with a verbal description of the project, its objectives, and requirements for participation and completed informed consent documents approved by the Institutional Review Board (IRB), per university policy, prior to any experimentation. Participants completed a medical history questionnaire suggested by the American College of Sports Medicine to screen participants for potential heart or blood conditions that would place the participants at undue risk during experimental protocols. Participants also completed a custom demographic questionnaire and a questionnaire to assess participant's habitual physical activity. Participation in the study was strictly voluntary and participants were compensated at a rate of $15 per testing session.

Maximum Heart Rate Assessment

For those participants that passed the medical screening, a graded exercise test (GXT) was used to assess physical fitness level and estimate maximum heart rate. The GXT was performed on a motorized treadmill using a modified Balke protocol. The Balke protocol specifies that after a 5-minute warm up period (5% gradient at $5 km \cdot h^{-1}$), the gradient will be increased by 2.5% every 2 minutes until the participant feels fatigued. During the GXT, heart rate was continuously monitored (S810 Polar Heart Rate Monitor) and maximum heart rate (HR_{max}) was recorded. During the GXT, participants were not allowed to use the treadmill handles at any time and were verbally encouraged to continue the test until exhaustion.

Dependent Variables

Three dependent variables were considered: recovery time, reduction in core body temperature, and reduction in heart rate. Recovery time was recorded as the amount of time required for the participants core body temperature ***and*** heart rate to return to pre-exercise conditions. Reduction in core body temperature was calculated as the average reduction in core body temperature per minute over the recovery period. Core body temperature assessments were taken every minute during recovery using an infrared ear scanner (Omron). Reduction in heart rate was calculated as the average reduction in heart rate per minute over the recovery period. Heart rate assessment was continuous and was monitored on a computer throughout recovery using a Polar Heart Rate Monitor (S810).

Independent Variable

The independent variable for this phase was the vest or recovery test being performed. Each participant completed three trials to assess recovery rate: (1) exposure and recovery with no vest (Base), (2) exposure and recovery with either the HeatShield (HS) or AirVest (AIR), and (3) exposure while wearing a discharged HeatShield and recovery with either the HeatShield (HS_{dhs}) or AirVest (AIR_{dhs}).

Participants were randomly assigned to recovery groups, with the exception that all participants completing the Base condition for comparison purposes.

Heat Exposure Protocol

The previous night and the morning of testing, participants were instructed to consume a minimum of 1-liter of a non-caffeine beverage to ensure normal hydration. The heat exposure protocol consisted of continuous walking on a motorized treadmill at 5 $km \cdot h^{-1}$ and 0% gradient. The ambient environment during heat exposure was controlled in an environmentally controlled room at 35^oC (95^oF) with humidity and wind speed constant at 40% and 0.9 $m \cdot sec^{-1}$ (2 mph) respectively.

Participants were required to wear a standard fire fighters ensemble (jacket and pants) over a cotton shirt, shorts, and with tennis shoes. This ensemble was chosen to ensure standardization across participants, to minimize the amount of body heat that escaped during the test sessions, and to simulate a "worst case scenario".

Core body temperature (T_{co}) was measured using infrared ear temperature scans at a sampling frequency of 500 Hz. Temperature assessments were taken every 2 minutes during exercise and every minute during recovery. During assessments, participants were allowed to rest their hands on the handrails for stability. An experimenter "tugged" on the participants' ear upward and back to straighten the ear canal and improve reading consistency. A total of three scans were taken every assessment and the average was used as T_{co}. Heart rate (HR) was assessed continuously during both exercise and recovery.

Procedure

Upon arrival and the completion of the consent forms, the medical screening, personal demographic, and physical activity questionnaires were completed. Participants then scheduled a time for the completion of the GXT. Recovery test sessions were scheduled following the GXT assessment and were no less than 48 hours apart and no more than 2 weeks apart.

At each test session, participants were fitted with all data collection equipment and asked to rest in a seated position in a thermal neutral environment for 5 minutes, after which resting heart rate and core body temperature was recorded. Participants were fitted with the appropriate vest and the ensemble, entered the environmental room, and remained seated for 20 minutes to become acclimated to the room conditions. Participants began exercise and continued until either 1 hour was expendedor until reaching one of three safety criteria:

1. T_{co} reaches 39°C,
2. HR reaches 85% of individual maximum as determined through the GXT test,
3. or subject experiences any adverse symptomology (dizziness, nausea, weakness, chills, absence of sweat) or volitional (subjective) fatigue.

After completion of the experimental condition, participants were immediately placed in a thermal neutral room and fitted with the appropriate recovery vest. During recovery, the ensemble was removed and the participant remained seated until heart rate ***and*** core body temperature values returned to resting levels.

Statistical Analysis

All variables were statistically analyzed by a repeated measures analysis of variance, with a significance level of α=0.10. Tukey's multiple comparison tests were used to identify specific differences between testing/vest conditions.

Phase III: Human Performance Testing and Usability Assessment

Participants

Participants identified in Phase II completed Phase III.

Dependent Variables

The dependent variables considered included: heart rate increases per minute (HR), core body temperature increases per minute (T_{co}), rate of perceived exertion (RPE) increases, maximum RPE rating, and exercise duration (time). HR was assessed continuously during the exercise protocol using the S810 Polar Heart Rate Monitor. T_{co} was assessed every other minute throughout the test session. T_{co} was the average of three ear scans (as described earlier). Every 5 minutes participants were asked to provide an estimate of how hard they were working using the Borg's Perceived Level of Exertion Scale (RPE) (ranging from 0=no effort to 10=maximal effort). Participants were shown a copy of the scale and asked to orally rate their RPE.

Following each testing condition, participants completed a short questionnaire asking them to subjectively rate comfort and usability factors of each garment. Usability of the vests was assessed using nine questions including ease of donning, movement comfort, fit on the body and underneath the uniform, interference with exercise, adjustability, increase in work time, use of the vest daily, and overall vest performance. Participants used a 5-point scale ranging from 1=strongly disagree to

5=strongly agree to rate each question. After the last testing session, participants were asked to force rank the vests from most preferred to least preferred.

Independent Variable

The independent variable was the vest used during exercise. Each participant completed three trials: (1) HeatShield, (2) AirVest, and (3) IsoTherm (Bullard). Testing was randomized across participants using a balanced Latin Squares design. Test sessions were scheduled no less than 48 hours apart and no more than 2 weeks apart.

Heat Exposure Protocols

The previous night and the morning of testing, participants were instructed to consume a minimum of 1-liter of a non-caffeine beverage to ensure normal hydration. The heat exposure protocol consisted of continuous walking on a motorized treadmill at 5 $km \cdot h^{-1}$ and 0% gradient. The ambient environment during heat exposure was controlled in an environmentally controlled room at 35°C (95°F) with humidity and wind speed constant at 40% and 0.9 $m \cdot sec^{-1}$ (2 mph) respectively.

Participants were required to wear a standard fire fighters ensemble (jacket and pants) over a cotton shirt, shorts, and with tennis shoes. This ensemble was chosen to ensure standardization across participants, to minimize the amount of body heat that escaped during the protocols, and to simulate a “worst case scenario”.

Procedure

Upon arrival, participants were fitted with all data collection equipment and resting heart rate and core body temperature assessment were taken after participants rested in a seated position for 5 minutes in a thermal neutral room. Participants then entered the environmental room and rested in a seated position for 20 minutes to acclimate to room conditions, after which they were fitted with a fully charged cooling vest and ensemble. Exercise began immediately and continued until one of the safety criteria were met (discussed previously) or testing duration reached 1 hour.

After completing the test session, participants were escorted to a thermal neutral room to rest for an unspecified amount of time. After participants felt rested, they completed the 9-question usability questionnaire. On the last day of testing, participants ranked each of the three vests as 1, 2, or 3, with 1=most preferred vest and 3=least preferred vest.

Statistical Analysis

HR, T_{co}, RPE, maximum RPE, and exercise duration were statistically analyzed by a repeated measures analysis of variance, with a significance level of α=0.10. Usability and final ranking data were analyzed using one-way analysis of variance, α=0.10. Tukey's multiple comparison tests were used to identify specific differences between testing/vest conditions. Trends in each variables and ratings of thermal comfort were also visually inspected.

RESULTS

Phase I: Cooling Capacity Assessment of ClimaTech Safety Cooling Vests using Thermal Manikins

Results from the Natick Soldier Center identified that the cooling time of both the HeatShield and the IsoTherm were identical, though the HeatShield provided more cooling capacity (the amount of cooling was greater for the HeatShield) (Table 1, Figure 1 and Figure 2). TM testing results on the AirVest indicate that at 30% and 80% relative humidity, cooling capacity is 312 and 359 Watts respectively.

Table 1. Cooling capacity values using the TMs

Vest	Cooling Capacity	Cooling Time
HeatShield	152 Watts	21 minutes
IsoTherm	139 Watts	21 minutes
AirVest	312, 359 Watts*	Unlimited

* Values represent cooling capacity at 30% and 80% relative humidity respectively

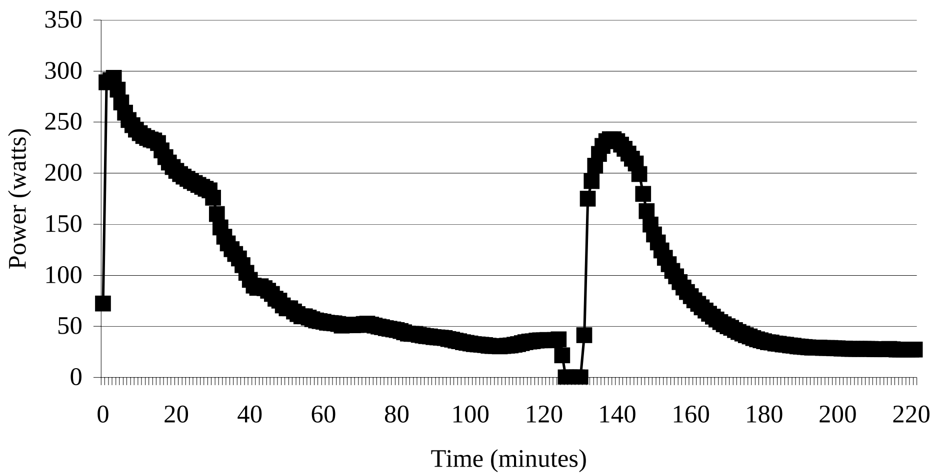

Figure 1. Heat Shield TM Tests Results

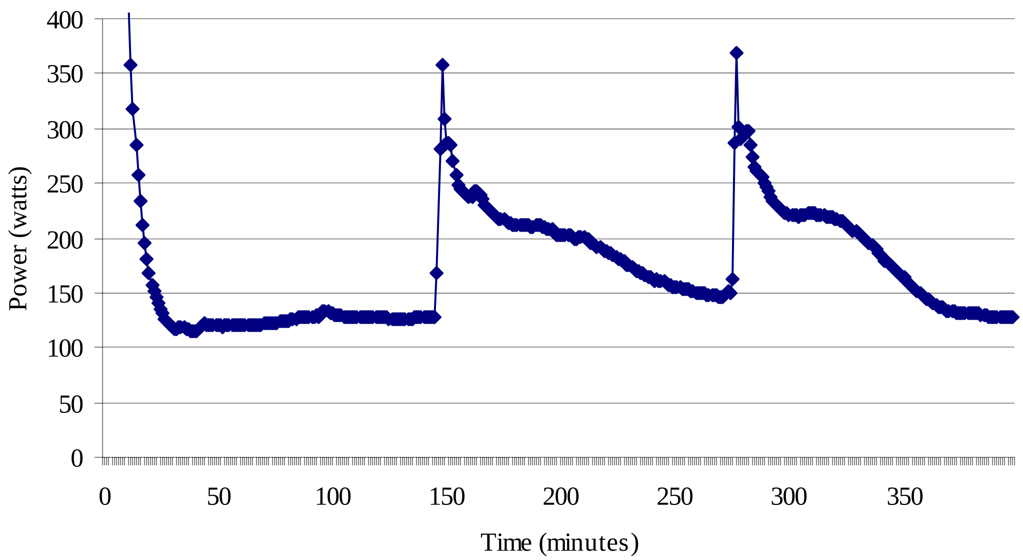

Figure 2. IsoTherm TM Test Results

Comparing these results with similar studies indicates that the cooling capacity of the vests were comparable to those developed specifically for military operations (cooling capacities ranged from 85 watts to 160 watts) (Masadi et al, 1991). The cooling time of the vests presented above, however, are significantly less than any of the products previously tested under near identical circumstances (cooling time ranged from 40 minutes to 120 minutes for non-continuous cooling vests). These results support the use of commercially available micro-climate cooling products for short durations of time.

Phase II: Recovery Rates Associated with ClimaTech Safety Cooling Vests

Recovery time and core body temperature (T_{co}) reductions per minute were significant by vest type/condition (p = 0.08 and p=0.07 respectively) (Table 1, Figure 3 and Figure 4). Recovery time was shortest for those conditions in which the AirVest was tested. These times were statistically shorter than trials involving the HeatShield. The use of any cooling vest resulted in significantly shorter recovery times than recovery without the use of a cooling vest. Results also indicated that T_{co} was reduced the greatest in the AIR_{dhs} condition. T_{co} was reduced the least in the HS_{dhs} trial, and no statistically significant differences were found between the other conditions. No significant differences were found in heart rate (HR) reductions across the trials (p=0.66). These findings provide support for the use of any cooling vest in reducing core body temperatures and recovery times to return body temperatures and heart rates to within pre-exercise levels.

Table 1. Descriptive statistics for the recovery trials. Values are mean (standard deviation). Groupings indicate which vests/trials resulted in similar findings. Those vests/trials with the same letter do not differ significantly from each other. Non-significant findings do not have a grouping

Trial/ Vest	**Recovery time (min)**	**Group**	**T_{co} reduction (°F)**	**Group**	**HR reduction (bpm)**
HS	20.41 (2.71)	A	0.0748 (0.0147)	B	3.08 (0.91)
HS_{dhs}	17.71 (2.58)	A	0.0465 (0.0136)	C	3.74 (0.84)
AIR	15.65 (3.17)	B	0.0686 (0.0182)	B	3.86 (1.16)
AIR_{dhs}	15.33 (3.62)	B	0.1174 (0.0218)	A	5.94 (1.40)
Base	22.77 (2.56)	C	0.0541 (0.0135)	B	3.07 (0.84)

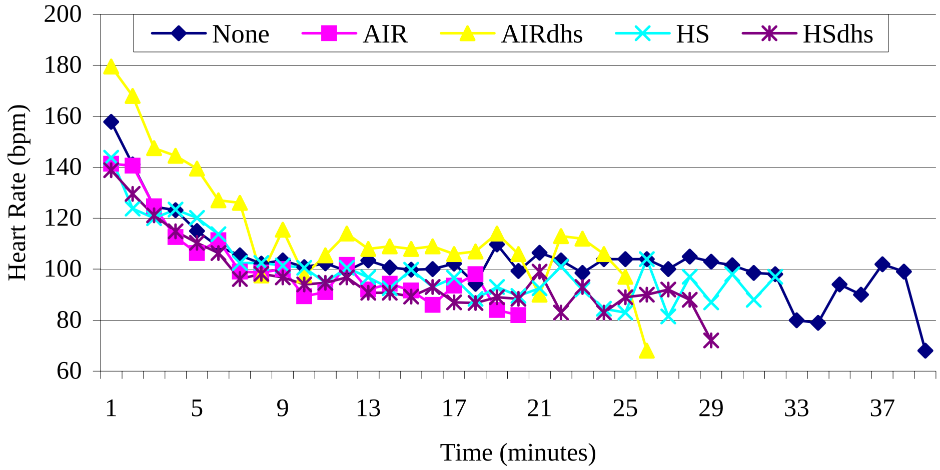

Figure 3. Mean decrease in heart rate by recovery trial.

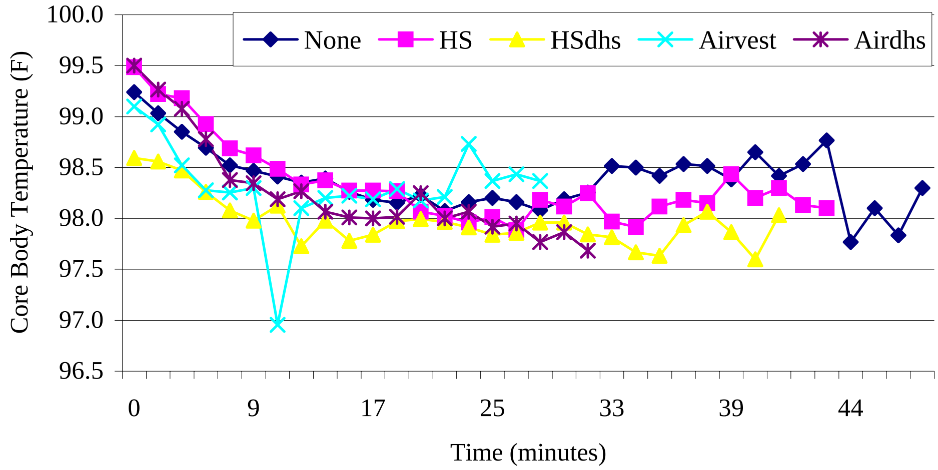

Figure 4. Mean decrease in core body temperature by recovery trial.

Phase III: Human Performance Testing and Usability Assessment

Only increase in core body temperature was significant by vest type (p=0.09) (Table 2, Figure 5 and Figure 6). Both the AirVest and HeatShield resulted in significantly lower increases in core body temperature than the IsoTherm, though they were not different from each other. Heart rate increase (p=0.56), test duration (p=0.45), RPE (p=0.99), and maximum RPE rating (p=0.66) were not significant by vest type (Table 2). These findings support the use of cooling vests during light to moderate exercise to reduce increases in core body temperature, which will result in longer work duration times, improved employee comfort, and a potential reduction in the risk of heat related injuries and illnesses.

Table 3. Descriptive statistics for the human performance trials. Values are mean (standard deviation). Groupings indicate which vests/trials resulted in similar findings. Those vests/trials with the same letter do not differ significantly from each other. Non-significant findings do not have a grouping.

Vest	T_{co} increase (^oF)	Group	Duration (min)	HR increase (bpm)	RPE increase	Max RPE
AirVest	0.0276 (0.0269)	A	29.75 (8.32)	4.0247 (1.2197)	0.0461 (0.1375)	3.09 (0.45)
HeatShield	0.0341 (0.0268)	A	27.88 (8.32)	4.0705 (1.2197)	0.0425 (0.1375)	2.85 (0.45)
IsoTherm	0.0679 (0.0269)	B	30.50 (8.32)	3.3452 (1.2197)	0.0421 (0.1375)	2.79 (0.45)

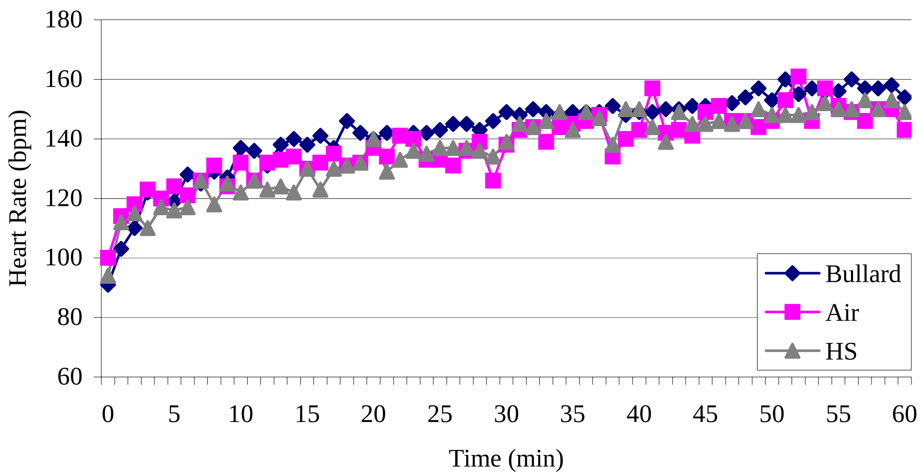

Figure 5. Mean increase in heart rate by vest type.

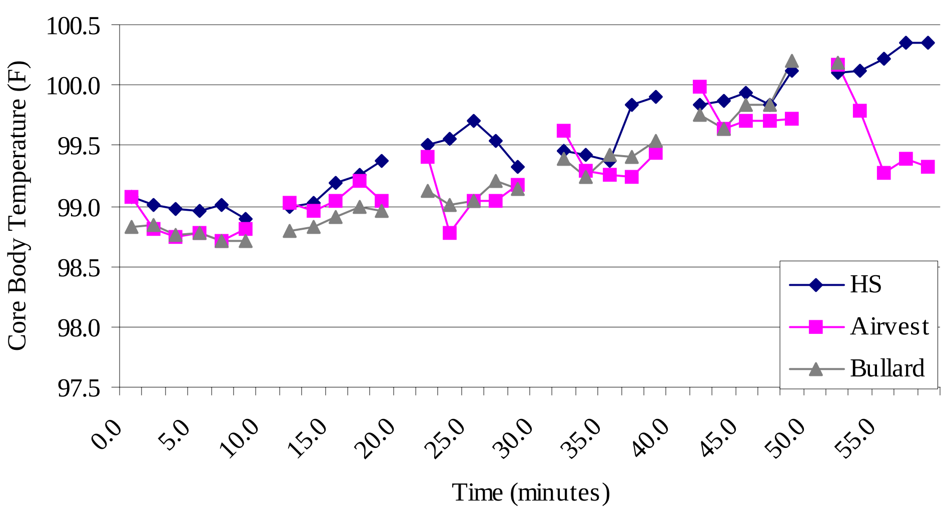

Figure 6. Mean increase in core body temperature by vest type.

Usability results are presented in Table 3. In general, the HeatShield and AirVest were rated superior to the IsoTherm for all questions. For vest donning, movement comfort, and fit underneath the uniform, the HeatShield and AirVest received significantly higher ratings than the IsoTherm, but ratings between the HeatShield and AirVest were not significant. Participants rated the body fit of the HeatShield significantly higher than the other two vests, and body fit of the AirVest significantly higher than the IsoTherm. The HeatShield was also rated highest in terms of daily usage over the other vests, with the IsoTherm receiving the second highest rating which as significantly higher than the AirVest rating. Participants did not perceive any differences between the vests in terms of interference with the exercise, adjustability, increased work time, or overall performance. The HeatShield was by far the most preferred cooling vest with 75% of the participants giving a rank of 1. No differences were found in the mean rankings for the AirVest or Bullard.

Table 3. Usability mean scores and final rankings. Values are mean (standard deviation).

Question	HeatShield	AirVest	Bullard	p-value
1. It was easy to don the vest	4.50 (0.53)	4.25 (0.71)	3.38 (1.41)	**0.07**
2. I was able to move comfortably while wearing the vest	4.00 (0.53)	4.25 (0.71)	3.00 (1.20)	**0.02**
3. The vest fit my body well	4.38 (0.74)	4.00 (0.76)	3.13 (1.25)	**0.04**
4. The vest fit well underneath the uniform	4.50 (0.53)	4.25 (0.71)	3.25 (1.16)	**0.02**
5. The vest did not interfere with performing the exercise	4.25 (1.03)	4.00 (0.93)	3.25 (1.16)	0.16
6. Adjustability of the vest was sufficient	4.00 (0.76)	3.88 (0.64)	3.25 (1.04)	0.17
7. I feel I could work longer if I used the vest regularly	4.25 (0.46)	3.13 (1.46)	3.50 (0.93)	0.11
8. I would use this vest daily if it was available	4.13 (0.64)	2.88 (1.36)	3.13 (0.83)	**0.05**
9. I would rate the overall performance of this vest as (0=worst, 5=best)	4.13 (0.64)	3.38 (1.19)	3.25 (0.71)	0.12
Final Rank	1.38 (0.74)	2.38 (0.74)	2.25 (0.71)	**0.02**

DISCUSSION

The objectives of this study were to: (1) determine cooling capacity performance of selected commercially available micro-climate cooling vests using thermal manikins (TMs), (2) evaluate recovery rates associated with ClimaTech Safety cooling vests following heat exposure while performing light exercise, and (3) provide performance assessment data using human subjects (quantitative physiological response assessments and qualitative comfort and usability assessments) while performing light exercise. Results pertaining to objective 1, cooling capacity performance, indicated that it is expected that persons wearing the HeatShield or the IsoTherm vest will benefit from wearing these products for 21 minutes. After that time, while persons may still report sensations of cooling, the ability of the vests to keep core body temperatures within a safe range will be depleted. These findings differ significantly from previous findings by ClimaTech Safety, Inc. Discussions with Natick personnel indicated that the differences are due to the cutoff point of 100 watts of cooling, which has been found to be critical in reducing core body temperatures. Based on these findings, possible modifications to the design of the HeatShield may be needed to increase the cooling time of the vest. For example, having the vest become a more enclosed or complete unit (e.g., more like a shirt) may promote conservation of cooling capacity of the vest. The current bib-like design may allow too much of the cooling to escape before being transferred to the human operator.

Findings of the recovery rate phase provide support for the use of micro-climate cooling products to help persons return to pre-exercise physiological levels under extreme temperature conditions. Reductions in core body temperatures were found to reduce to normal levels much faster when any cooling vest was used. Additionally, the time required for both heart rate and core body temperature to return to normal levels was shorter when a cooling vest was used. Heart rate (HR) reductions were not effected by the use of a cooling vest during recovery. This finding was expected, as the majority of heart rate reductions should be related to the cessation of exercise. The other primary role of increase heart rate following exercise is to dissipate heat from the body. The use of a cooling vest would reduce the need for the heart to work in this capacity. There is a trend in the data associated with HR reductions. The trials associated with cooling vests had higher mean values for HR reductions than the Base trial, with the exception of the HS trial. Increasing the sample size may reveal that this trend is in fact significant.

Results associated with the human performance testing found that only core body temperature increases were significant across the vests, with the AirVest and HeatShield resulting in significantly lower increases in core body temperature over the test duration. This finding supports the use of micro-climate cooling products during work tasks in extreme temperatures to reduce the effects of the environment on the human operator. With a reduced core body temperature, persons should be able to work for longer periods of time without experiencing undue stress or suffering from a heat related injury or illness. Again, HR increases were not expected to differ significantly given that the exercise remained consistent across vests and the weight and style of the vests were very similar. This same rationale is used to explain the lack of significance in rates of perceived exertion. Given the similarities, it was expected that participants would not perceive differences in the workload experienced.

Usability of the AirVest and HeatShield were, in general, superior to the IsoTherm vest. A major criticism of the IsoTherm vest was the bulkiness and discomfort associated with the initial use of the ice packs. Efforts were made to ensure the ice packs were frozen flat without odd angles or protrusions. However, the frozen ice packs were still uncomfortable for the participants. The major criticism of all the vests was the weight. Each of the vests weighed approximately 10 lbs when fully charged. Participants expressed concerns about using any vest for prolonged periods of time. A psychophysical study would need to be performed on experienced workers to determine if the weight of the vest would in fact result in significant increases in energy expenditure and affect perceived work durations.

Overall, the findings of this project support the use of micro-climate cooling products for persons working in extreme temperature conditions. Potential benefits for the recovery of persons following exposure to extreme conditions are promising in terms of reducing core body temperatures to normal levels in shortened periods of time. Vest redesign considerations may improve the performance of the vests in terms of cooling time. However, the current design is perceived by persons to be comfortable and conducive to extended wear.

Reference

Masadi, R., Kinney, R., and Blackwell, C. (1991). Evaluation of five commercial microclimate cooling systems for military use. United States Army Natik, Research, Development and Engineering Center.