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Cooling Suits, Physiological Response, and Task Performance in Hot Environments for the Power Industry

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Heat stress on workers working outdoors in the power industry may result in fatigue and deterioration in task performance. This research collected and analyzed data on task performance of workers working indoors and outdoors with and without a cooling suit. The task performance was compared on the basis of heart rate, oxygen consumption, tympanic temperature, subjective responses, productivity, and error rates. Based on One-Way Analysis Of Variance (ANOVA) results, a significantly lower estimated working oxygen consumption was observed ($p < .001$*) when the cooling suit was worn. The productivity was higher while workers wore the cooling suit as compared to no cooling suit (*$p = .011$*) whereas the error rates were significantly lower (*$p < .001$*). Also a significantly lower self-reported discomfort was observed in the neck and shoulders while working wearing the cooling suit (*$p = .004$*). This study concluded that wearing a cooling suit while working outdoors was associated with physiological benefits as well as improved task performance of the study participants.*

heat stress   energy expenditure   task performance   cooling suit

1. INTRODUCTION

In the USA it has been estimated that some 5 to 10 million workers are exposed to heat stress annually [1]. A subjective survey by the French Ministry of Social Affairs indicated that 16.6% (3 million) of French workers complained of daily or frequent heat exposure at work [2].

Workers in high temperature environments are prone to fatigue, and heat strain can result from the physiological responses to the imposed heat stress [3]. Weariness and physical weakness are the first signs of fatigue in a hot environment [4]. Additional strain appears to be imposed on participants working at environmental temperatures outside the 22–28 °C (71.6–82.4 °F) range based on working heart rate (*HR*) [5].

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Work and thermal environments which elevate the body temperature have been shown to adversely affect task performance and contribute to fatigue [6]. At body temperatures substantially higher than the optimal levels (36.5–37.5 °C; 97.7–99.5 °F), both physical and mental performance may deteriorate [7]. In addition, prolonged heat strain may impair mental and psychomotor functions, thereby affecting performance [7].

Researchers have observed *HR* increase of 48 beats/min while a task is performed in a hot environment (32–37.22 °C; 90–99 °F) and in comfortable surroundings (22 °C; 72 °F) [8]. Also a significant deterioration in task performance and an increase in reaction time is observed when subjects are exposed to an external environment of 35 °C (95 °F) and 75% relative humidity [9]. Extreme thermal environments have also been shown to affect performance at certain mental tasks [10]. In addition to the temperatures in warmer climates the overhead power lines are conductors (if grounded) with operating temperatures as high as 75 °C (167 °F).

To control human heat stress and strain in hot environments a functional approach is to provide a personal clothing ensemble to build up a cooler microclimate for auxiliary body cooling [11]. Different types of heat protective personalized clothing ensembles (e.g., ice vest, air- or water-cooled vests, wettable covers) have been developed to conserve a comfortable microclimate [11].

A number of research projects have been undertaken to understand and reduce the effects of heat stress on the worker at work in high temperature environments [6, 8, 9, 11, 12, 13, 14, 15, 16]. This research effort proves to be different in the sense that it measured the differences in the subjects' physiological responses and task performance while they performed simulated work tasks indoors, outdoors without the cooling suit, and outdoors with the cooling suit.

2. METHODS

2.1. Subjects

Twelve males participated in this study. All of them were graduate students from India, studying at Lamar University, USA. Each subject completed an informed consent form, a coronary risk questionnaire [17], and a health risk appraisal. The study was approved by the Institutional Review Board for testing human subjects at Lamar University.

In addition resting *HR* and resting blood pressure (*BP*) were measured with an Omron digital BP monitor (Omron Healthcare Inc., USA). Two resting *HR* and *BP* measurements were taken for each participant. All participants met the screening criteria [17].

2.2. Anthropometric Measures

Various anthropometric measures such as stature, body height, knuckle height, acromial height, and overhead reach height were taken for all subjects.

2.3. Cooling Suit

The shirt had over 15 m (50 ft) of small capillary water tubing sewn onto the front and back with the areas between the tubing free for easy air exchange between the suit and the external environment (suit weight ~1.4 kg or 3.0 lb). Chilled water from a ~15-L (16-qt) ice chest reservoir re-circulated in a closed-loop through the suit by means of a 12-V pump (F.A.S.T. Race Products, USA).

2.4. Submaximal Arm Ergometer Test

The power utility workers use their arms and hands to perform the work on the overhead power lines. Since it was not feasible to measure the oxygen consumption (V_{O2}) of the participants while they were working on the simulated power line, a submaximal arm ergometer test, under each of the three testing conditions, was conducted for each participant.

All 12 participants had three trials on the arm ergometer. Each participant was tested under three test conditions:

- indoors without the cooling suit (control group);
- outdoors without the cooling suit (typical work environment without intervention); and
- outdoors with the cooling suit (typical work environment with intervention).

The order for the tests was randomly selected. The indoor tests were conducted in the Human Factors and Ergonomics Laboratory in the Lucas Engineering Building at Lamar University. The outdoors testing was performed in the courtyard, adjacent to the Human Factors and Ergonomics Laboratory. Each participant was randomly assigned to don the cooling suit and provided ample time to familiarize himself with cranking the arm ergometer at a constant speed.

Each participant's age-related predicted maximal *HR* was calculated along with their estimated 85% maximal *HR* using the Karvonen formula [18]. The participants were then asked to perform a submaximal arm ergometer test to estimate their maximum V_{O2} rate. The participant's *HR* was monitored using the Polar Vantage NV heart watch (Polar CIC, Inc., USA) and V_{O2} was measured using the OXYLOG II V_{O2} measurement system (Morgan Scientific, Inc., USA). The tympanic temperature, t_{ty}, of the participant was measured using the Braun Thermoscan Pro 3000 tympanic thermometer (Welch Allyn, Inc., USA) and the Heat Index was measured using the QUESTemp °34 thermal environment monitor (Quest Technologies, Inc., USA). The participants performed the arm ergometer test on the Monark Rehab Trainer 881 E (Monark Exercise, AB, Sweden).

A modified five-stage continuous test protocol was used for the purpose of the submaximal test [19, 20]. Starting with an initial load of 15 W, it utilized load increments of 10 W after the first 3 min, and increments of 15 W every 3 min thereafter, while maintaining a constant arm cranking rate of 50 revolutions/min (RPM).

Prior to the test, 4 min of resting *HR*, *BP*, and t_{ty} data were noted. The participant then practiced arm cranking in cadence with a metronome. This metronome with its auditory signal was also used to maintain the correct cranking rate during the test. A digital readout of the cranking speed of the arm ergometer also helped the participant in maintaining the desired arm cranking speed. The test was discontinued when the participant had completed the final stage, when his *HR* reached the calculated 85% maximum *HR*, or the participant chose to stop the test.

HR and V_{O2} were recorded at the end of every 3 min in the protocol. These data points were used to establish a linear relationship between *HR* and V_{O2} for each participant in each of the three different test conditions. Also, t_{ty} at the end of the test was noted as final t_{ty}.

2.5. WBGT assessment

According to the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs), heat exposure in the heat index range of 32.2–37.8 °C (90–100 °F) may result in a heat-related illness. Since workers in the power utility companies work all through the day, the participants were tested in the heat index range of 32.2–37.8 °C (90–100 °F) outdoors.

2.6. Power Utility Task Simulation Trials

For the simulated power utility trials, only 10 participants were tested due to unexpected cool weather. The power utility task simulation trials were conducted both indoors and outdoors. Similar to the arm ergometer tests, the power utility tasks were performed under three test conditions:

- indoors without the cooling suit (control group);
- outdoors without the cooling suit (typical work environment without intervention); and
- outdoors with the cooling suit (typical work environment with intervention).

Again the trials were randomized. A mobile mock setup of the power line complete with two cross arms, insulators, aluminum conductors steel reinforced (ACSR), and the boom bucket was created. Each trial lasted approximately 30 min and was randomly selected. Each participant completed a body-part discomfort survey form

Figure 1. The power utility simulation trial outdoors.

before each trial. Prior to the test, 4 min of resting data such as *HR*, *BP*, and t_{ty} were noted.

The amount of work prescribed to be completed in each 30-min trial was determined with the assistance of Lamar Institute of Technology's Service Line Technician Program. To establish a consistent pace, each participant was provided ample time to become proficient in performing the required tasks in the allotted amount of time prior to actually performing the trials. Also, during the trials the participants were not advised as to the elapsed time (or time remaining) to assist in maintaining the learned pace in the pretest training period.

During these procedures the subjects were videotaped. Those data were used for performance measurement evaluation. The body temperature response of the subjects was recorded with and without the cooling suit. The participants performed the trials indoors, outdoors with the cooling suit, and outdoors with the cooling suit (Figure 1).

The participant was randomly assigned to don the cooling suit and provided enough time to familiarize himself with the tasks to be performed (in case wearing the suit posed a difficulty). The performance of each subject was monitored as he became proficient and peaked in his task skill levels with the cooling suit and these measures of performance became statistically similar to those without cooling suit measures.

By working with representatives from the power service industry, as well as with Lamar Institute of Technology's Service Line Technician Program Director, a sequence of operations was developed to simulate the tasks commonly performed by power linemen. The sequence of operations included donning all personal protective equipment and other equipment (e.g., shoulder insulation sleeves, rubber gloves, a hard hat, safety glasses, tool belt, lineman's pliers, wrench, washers, nuts, and prepared tie wire).

While in the bucket, the participants performed prescripted tasks such as

- installing and uninstalling smaller and larger insulators with bolts, washers, and nuts on the cross arms;
- constructing a top groove double tie using the ACSR; and
- cutting the wire using the lineman pliers.

This trial was designed to last for approximately 30 min. If the participant completed this cycle in less than 30 min, then he was asked to put on and take off additional smaller insulators until the 30 min had expired.

t_{ty} at the end of the trial was noted as final t_{ty} and the heat index was recorded during the trials.

Each participant completed a separate body part discomfort survey form after each trial. *HR* was recorded during each power utility task simulation trial and was stored as an *HR* file in the Polar HR monitor. These files were transferred from the monitor to the computer with the help of the interface.

V_{O2} was estimated using the linear regression equations developed with the appropriate arm ergometry tests: the indoor regression was used for the indoor simulation, the outdoor/with-suit regression was used for the outdoor/with-suit simulation, and the outdoor/without-suit regression was used to estimate V_{O2} of the outdoor/without-suit simulation.

2.7. Statistical Analysis

For each of the six analyses performed (*HR*, V_{O2}, t_{ty}, subjective responses, productivity, and error rates), One-Way Analysis Of Variance (ANOVA) was performed to determine if the particular variable under observation demonstrated any statistically significant differences. Tukey's HSD (Honestly Significantly Difference) mean separation procedure was used to perform post hoc analysis of the sample means at $\alpha = .05$ level of significance. The statistical analysis was performed using Minitab software[1] version 14.

2.7.1. HR *data*

HR data was recorded during each of the power utility simulation trials. Mean *HR* data over the 30-min trial duration was used for the purpose of analyzing the trials. For each subject these readings were tabulated for the three power utility simulation trials. Mean *HR* for each power utility trial outdoors was compared with each other and also with the control (power utility trial indoors).

2.7.2. V_{O2} *data*

The linear regression equation obtained through the three submaximal tests was used to identify the estimated V_{O2} for each power utility trial. The *HR* recorded during the power utility simulation trials was used in these equations to interpolate V_{O2} during each of the power utility simulation trials. This value of the estimated V_{O2} for the power utility trials was compared with each of the other trials outdoors and with the control (power utility trial indoors).

2.7.3. t_{ty} *data*

t_{ty} was recorded before the start and at the end of each power utility simulation trial. The difference in temperatures gave an indication of the rise/fall in temperature over the performance of the tasks in the trial. The initial temperature, final temperature, and the difference in temperature values were compared with each of the power utility trials outdoors, and with the control (power utility trial indoors).

2.7.4. Subjective response data

Each participant completed a subjective body-part discomfort survey before and after each trial. The survey was a continuous scale anchored by *none*, *moderate*, and *intolerable*, where *none* corresponded to 0 cm, *moderate* to 3.5 cm, and *intolerable* to 7 cm. The change in discomfort for each body part was determined by subtracting the before response from the after response. A negative value was indicative of a reduced level of discomfort trial.

2.7.5. Productivity data

The number of tasks completed provided a measure of the productivity for the purpose of the power utility trials. The tasks included attaching and detaching nuts and washers, making a top groove double tie, and putting on and taking off insulators. A complete work cycle comprised of each of these tasks being repeated twice with the exception of the insulators being put on and taken off 8 times. Table 1 provides the scores and the repetitions assigned to each of these tasks.

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[1] http://www.minitab.com/

TABLE 1. Scores for the Tasks of the Power Utility Trial

Task	Score	Repetition
Putting on and taking off nut and washer	10	2
Making top groove double tie	10	2
Putting on and taking off insulators	7.5	8

The complete work cycle accounted for a score of 100 points. Any unfinished work decreased the productivity score and additional insulators fastened and unfastened, over and above the completion of the work cycle, increased the productivity. The productivity score for each participant was compiled.

2.7.6. Error data

The number of slips, lapses, and out-of-sequence errors provided an account of the total number of errors made by the subjects. A slip was defined as an incorrect top groove double tie, an incorrect method of installing the insulator or nut, dropping the nut, washer, insulator, or a tool. A lapse was defined as failure to make a required turn in the tie, or failure to put the washer on. Out-of-sequence error was defined as failure to follow the sequence of operations, crossing the tie wire in the back instead of the front the first time, putting on the left insulator before the right insulator, or putting the nut on before the washer. The total number of errors observed was compared and contrasted with each of the power utility trials outdoors, and with the control (power utility trial indoors).

3. RESULTS

The following contains the descriptive statistics of the anthropometric data (Table 2) as well as the inferential statistics for the three power utility simulation trials for *HR*, estimated V_{O2}, t_{ty}, subjective data, productivity, and error rates. The results of ANOVA and Tukey's mean separation tests performed for these variables are provided and diagrammatic representations of these results are given in Figures 2–9.

3.1. Anthropometry

Descriptive statistics of the anthropometric data gathered on the 12 subjects is shown in Table 2.

3.2. ANOVA

Table 3 summarizes the results of the ANOVA procedure for *HR*, estimated V_{O2}, t_{ty}, subjective data, productivity, and error rates.

TABLE 3. Results of the Power Utility Trial Tests

Parameter	*p* Value	*s/ns*
Heart rate	.030	*s*
Estimated oxygen consumption	<.001	*s*
Initial tympanic temperature	.514	*ns*
Final tympanic temperature	.003	*s*
Difference in tympanic temperature	.004	*s*
Subjective measures: neck	.037	*s*
Subjective measures: shoulders	.004	*s*
Productivity	.011	*s*
Error rate	<.001	*s*

Notes. s—significant difference, *ns*—no significant difference.

3.3. *HR*

The *HR*s gathered during the three power utility trials were compared; they showed a significant difference ($p = .003$). As seen in Figure 2, the average *HR* was higher for the 10 subjects performing the power utility simulation trial outdoors when not wearing the cooling suit, as compared to working indoors, but was not significantly different from the power utility trial outdoors while wearing the cooling suit.

TABLE 2. Descriptive Statistics of Age, Weight, Height, Knuckle Height, Acromial Height, and Overhead Reach Height for All the Subjects

Subjects'	Age (years)	Height (cm; in.)	Weight (kg; lb)	Knuckle Height (cm; in.)	Acromial Height (cm; in.)	Overhead Reach Height (cm; in.)
M	24.3	171.8; 67.7	68.9; 151.9	77.9; 30.7	147.1; 57.9	212.9; 83.8
SD	1.4	7.8; 3.1	12.9; 28.4	4.2; 1.7	4.7; 1.8	11.7; 4.5

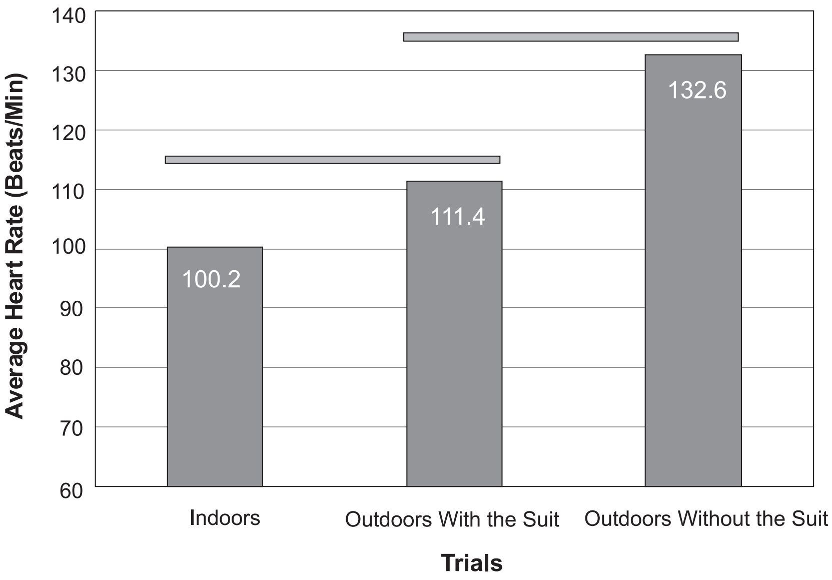

Figure 2. Mean heart rate of the participants for the three trials. *Notes.* Trials with a line over them are not considered significantly different.

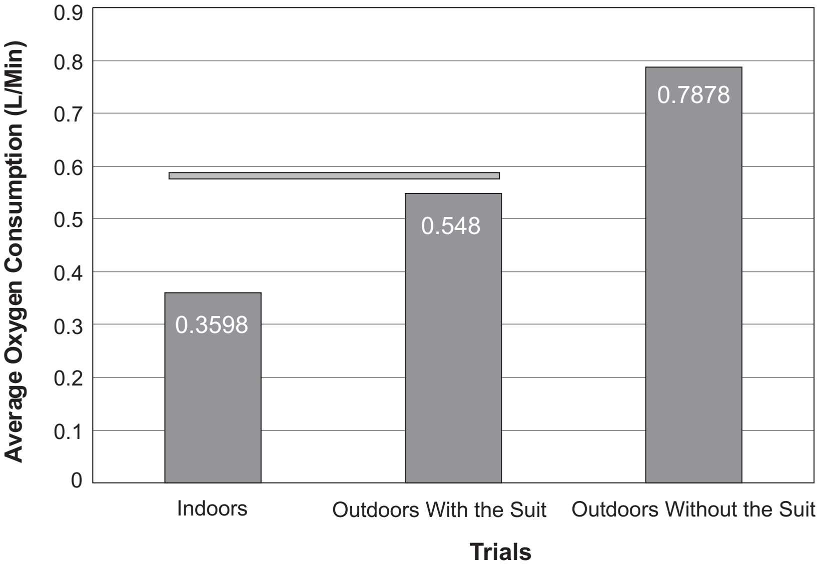

Figure 3. Mean estimated average oxygen consumption of the participants for the three trials. *Notes.* Trials with a line over them are not considered significantly different.

The power utility simulation trial outdoors with and without the cooling suit did not show a significant difference, even though the average *HR* was 21 beats/min lower when the cooling suit was worn. The results of the arm ergometer analysis closely resemble the power utility simulation tests.

3.4. Estimated V_{O2}

Based on each individual's *HR*, V_{O2} during each trial was calculated using the linear regression equation developed from each participant's *HR* and V_{O2} gathered during the ergometric tests. There was a significant difference between the power utility trials ($p < .001$). As shown in Figure 3, both working indoors and outdoors with the cooling suit resulted in a lower estimated working V_{O2} when compared to working outside without the cooling suit. No significant difference between testing indoors and outdoors with the suit was shown.

3.5. t_{ty}

Initial t_{ty} did not show a significant difference across the three power utility simulation trials ($p = .514$). As shown in Figure 4, final t_{ty} was significantly lower for both the indoors and outdoors trials with the cooling suit as compared to the outdoors trial without the cooling suit ($p = .003$). Figure 5 shows the difference in t_{ty} was significantly lower for both the indoors and outdoors tests with the cooling suit as compared to the outdoors test without the cooling suit ($p = .004$).

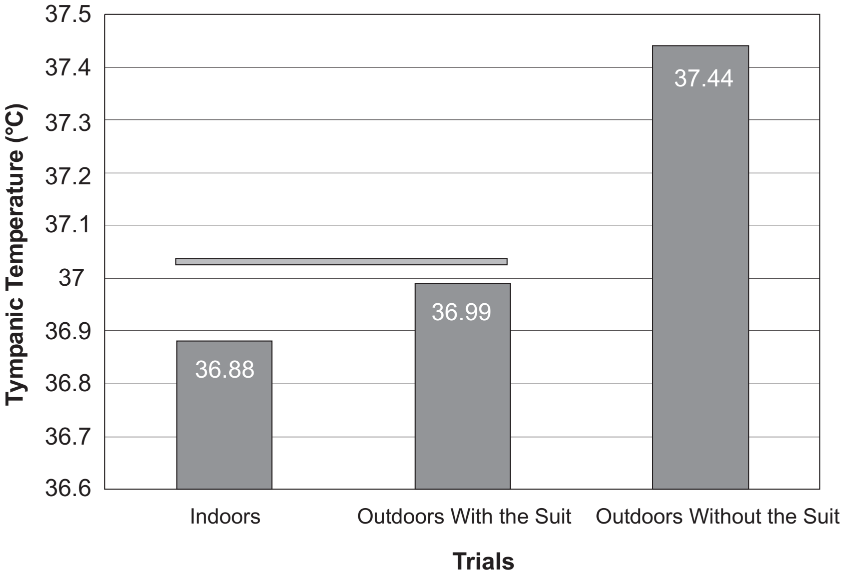

Figure 4. Mean final tympanic temperature of the participants for the three trials. *Notes*. Trials with a line over them are not considered significantly different.

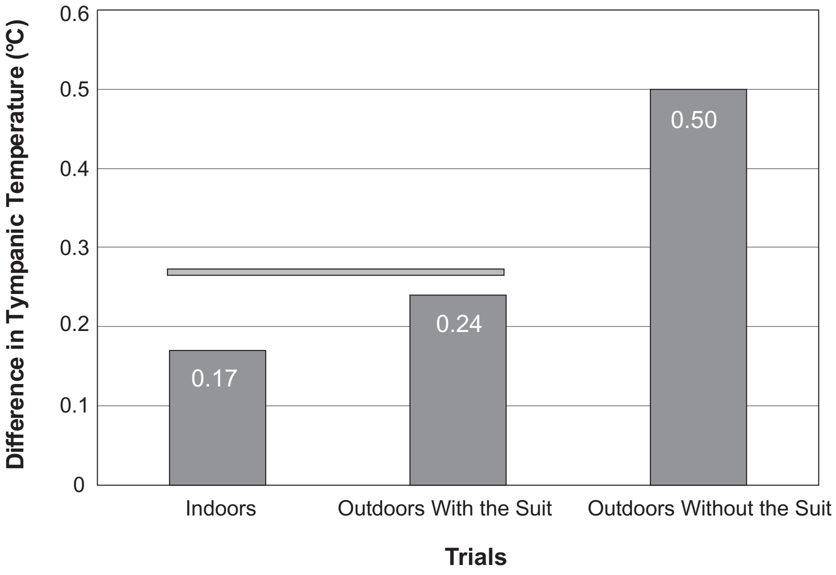

Figure 5. Mean tympanic temperature difference of the participants for the three trials. *Notes*. Trials with a line over them are not considered significantly different.

3.6. Subjective Responses

Discomfort levels were recorded at the eyes, neck, shoulders, upper back, upper arm, middle back, elbow, lower back, lower arm, wrists, hands, buttocks, thighs, knees, lower legs, and feet. Only neck and shoulder discomfort possessed a significant difference in discomfort levels ($p = .037$ and $p = .004$ respectively).

The average discomfort level at the neck for the indoors trial was significantly different from the outdoors trial without the cooling suit ($p = .037$), but was not significantly different from the outdoors trial with the cooling suit as shown in Figure 6. Figure 7 shows the mean recorded discomfort level at the shoulders was lower for the power utility simulation trial indoors and outdoors with the cooling suit as compared to outdoors without the cooling suit ($p = .004$). Subjective responses for the upper back, upper arm, middle back, elbow, lower back, lower arm, wrists, hands, buttocks, thighs, knees, lower legs, ankles, and feet lacked any significant differences across the three power utility simulation trials.

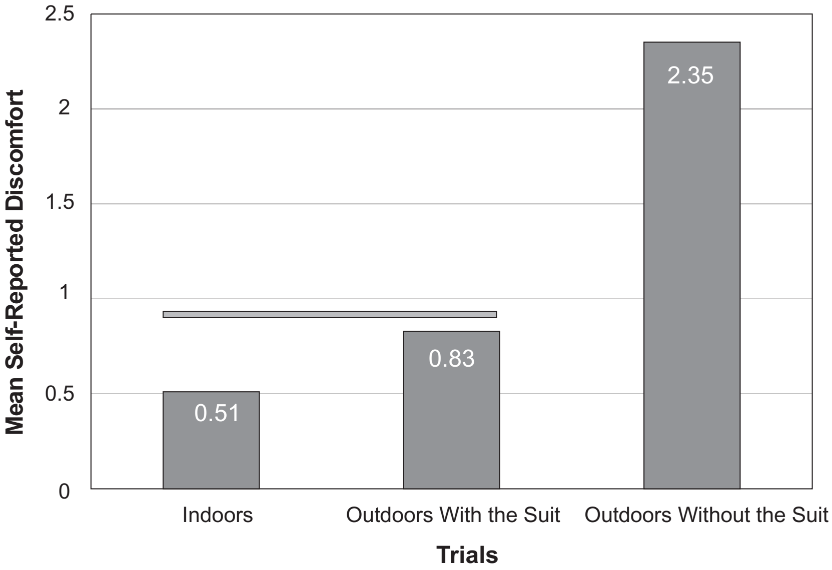

Figure 6. Mean self-reported neck discomfort of the participants for the three trials. *Notes.* Trials with a line over them are not considered significantly different.

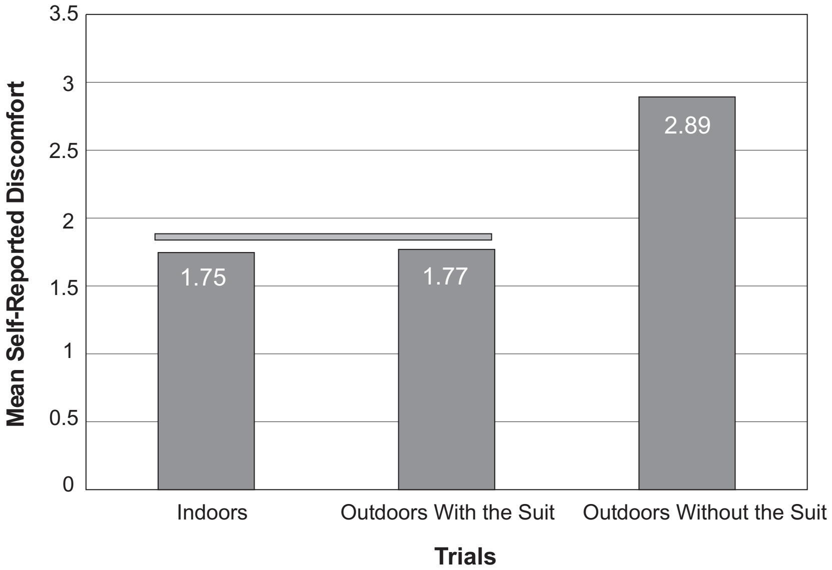

Figure 7. Mean self-reported shoulder discomfort of the participants for the three trials. *Notes.* Trials with a line over them are not considered significantly different.

3.7. Productivity

The total number of tasks completed gave an indication of the productivity of each subject, with the scores assigned to each task giving the numerical indication of the productivity. Figure 8 illustrates the mean productivity level was significantly higher for both the power utility simulation trial indoors and outdoors while the cooling suit was worn as compared to working outdoors without the cooling suit (*p* = .011).

3.8. Error Rates

The total number of errors recorded for each trial corresponded to the error rate for each power utility trial. Slips, lapses, and out-of-sequence errors were brought together as numbers and the data were compiled. The power utility trial indoors and outdoors with the cooling suit recorded significantly fewer errors as compared to working outdoors with the cooling suit (*p* < .001) (Figure 9).

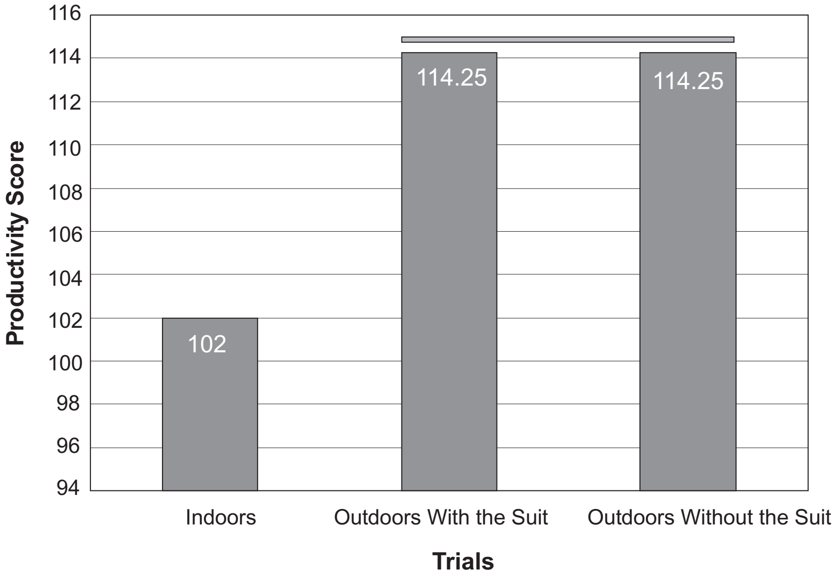

Figure 8. Mean productivity of the participants for the three trials. *Notes.* Trials with a line over them are not considered significantly different.

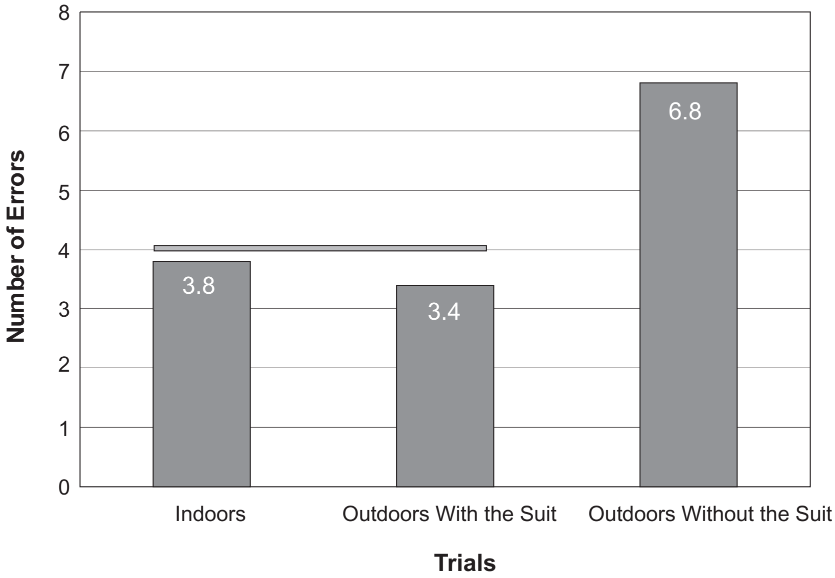

Figure 9. Mean number of errors of the participants for the three trials. *Notes.* Trials with a line over them are not considered significantly different.

3.9. Heat Index

The indoors trials were conducted in the range of 20.1–20.9 °C (68.1–69.7 °F); *M* = 20.5 °C (68.9 °F); *SD* = 0.15 °C (0.58 °F). The outdoors power utility simulation trials were conducted in the range of 32.3–34.0 °C (90.1–93.2 °F); *M* = 32.9 °C (91.2 °F); *SD* = 0.29 °C (0.96 °F).

4. DISCUSSION

HR was not significantly different in the power utility simulation trial while the subjects worked outdoors with and without the cooling suit, which was unexpected. However, there may be some practical significance in the fact that the average *HR* was 21 beats/min lower while they wore the cooling suit outside. It may be likely that such a response was due to the vasoconstriction of the vessels beneath the cooled area, improved venous return, and stroke volume and consequently decreased *HR* [21]. Previous studies cited suggest lower *HR* in lower temperature environments [8, 14].

The lower estimated V_{O2} for the outdoors trials with the cooling suit may be ascribed to the cooling effect of the cooling suit. Due to that effect, the response of the blood to serve as the cooling fluid in addition to transporting oxygen is slowed down. This in turn, lowers the amount of oxygen circulated/transported due to the reduction in the flow of blood needed to transport heat from the interior of the body to the skin to cool the body. This is in agreement with previous research [22].

A significant difference was noted for final t_{ty} between working outdoors with and without the cooling suit. It is also interesting to note that the cooling suit was associated with half of the body temperature increase as compared to working outdoors without the cooling suit. This may demonstrate the effectiveness of the cooling suit in assisting the body in maintaining a comfortable microclimate and body temperature. Since it allows removal of heat from the body surface to the environment, it reduces body heat storage. Therefore, it can be used as a supplemental or supportive device to the human body. This supports previous research findings [11, 23].

Using a cooling suit was also associated with a reduction in neck and shoulder discomfort which may have been caused by an increased physiological efficiency allowing the participant to better cope with the static overhead work required by such tasks. The use of the cooling suit also resulted in an increase in productivity and a reduction in error rates. Since the workers had low cumulative heat storage over repetitive work cycles, they were able to perform more work [9, 24].

The use of a cooling suit resulted in a rather impressive productivity increase of approximately 11% in the current study. In addition to the increases in productivity, approximately 44% fewer errors were made in the current study. In the field, these errors may have had to be reworked, further impacting the level of productivity. If even just a fraction of these task improvements were translated into the field, the positive financial influence would be significant.

Usually tethered cooling systems, such as the one under study, may have limitations when the subject is mobile. Other modified methods could be considered to easily deliver the cooling liquid to the cooling suit, permitting greater freedom of movement.

In using cooling suits, one may need to take care that with water temperature, at or below dew point, condensation of moisture around the tubes may augment heat loss through the skin through permeable clothing. When the cooling requirement is lower with low metabolic activity, higher flow rate of water may cause rapid chilling to wearer, resulting in cutaneous vasoconstriction and thermal discomfort [11].

Since the cooling suit may absorb ambient heat, its effectiveness may be improved by isolating it from the heat. If the cooling suit is not frequently used, the affluent water needs to be pushed out of the tubing for hygienic reasons. The effective use time of the cooling suit is limited by the amount of cold water available in the ice chest and the build-up of the water inlet temperature.

Another way to possibly keep the workers cool may be to ask them to wear the cooling suits during their rest breaks. Using a cooling suit may be very practical when working in high temperature environments. The present study on the effectiveness of using one at work in high temperature environments indicates that water cooled clothing holds high promise for wider use.

5. CONCLUSION

In accordance with the preceding data, V_{O2}, t_{ty}, subjective responses, productivity, the error rates, and previous research, it is reasonable to conclude there are physiological and performance benefits of wearing a cooling suit for a utility worker working outdoors in the hot environment [16]. The findings of this research are also similar to previous studies on cooling suits that were not specifically related to the power utility industry.

In summary, the cooling suit allowed this power utility task to be completed with less estimated energy expended, fewer errors, less discomfort, while resulting in higher productivity levels in a high heat index environment. In the current research, wearing the cooling vest while working in a high heat index environment was associated with physiological responses and productivity/error rates similar to when the same tasks were performed in an air conditioned laboratory.

6. RECOMMENDATIONS FOR FURTHER RESEARCH

The several outlets for further study based on this research include

- conducting more field studies to study the body temperature effects;
- increasing task duration;
- increasing observation duration of task performance;
- analyzing effects in additional heat index ranges;
- allowing the cooling suit to operate at maximum efficiency before the beginning of work;
- expanding into an entire scope of power utility industry tasks; and
- analyzing broader demographics of participants.

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