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Study of skin conductance and perceived discomfort of the hand/finger system under controlled atmospheric conditions

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ABSTRACT
The purpose of this study was to investigate the effect of factors such as temperature, relative humidity and physical exertion on the skin perspiration/moisture levels and subjective perceived discomfort ratings. The skin perspiration/moisture was measured using skin conductance meter. Nine male participants performed three hours of experimental trials that routinely required the physical exertion of lateral pinching. The skin conductance increased significantly with the increase in the temperature, relative humidity and presence of physical exertion. For the trials with physical exertion, the skin conductance was higher than similar trials with no physical exertion. A significant interaction effect of temperature and exertion on perceived discomfort was also observed. The results of this study seem to indicate that factors such as insulation, water permeability and cooing ability of the occupational gloves should be given priority in addition to the safety.

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Skin conductance; discomfort; glove microclimate; temperature; relative humidity

Relevance to human factors/Relevance to ergonomics theory

The overall findings of this study further demonstrate that for the occupational tasks performed with gloves under hot and humid conditions, factors such as insulation or water permeability of the occupational gloves should be given priority in addition to the safety. This study also validates future research advancing the ventilation capabilities of occupational gloves, especially spacesuit gloves, with the hopes of maintaining and controlling temperature and relative humidity within the microclimate. If these conditions are controlled properly then this study's research suggests it could aid in a reduction in risk of glove-related hand–finger injuries such as onycholysis.

Introduction

Hand and/or fingers have been repeatedly identified as one of the most frequently affected anatomical locations by acute work-related injuries (Macdonald, Sanati, and Macdonald 2012). The United States Department of Labor's Occupational Safety and Health

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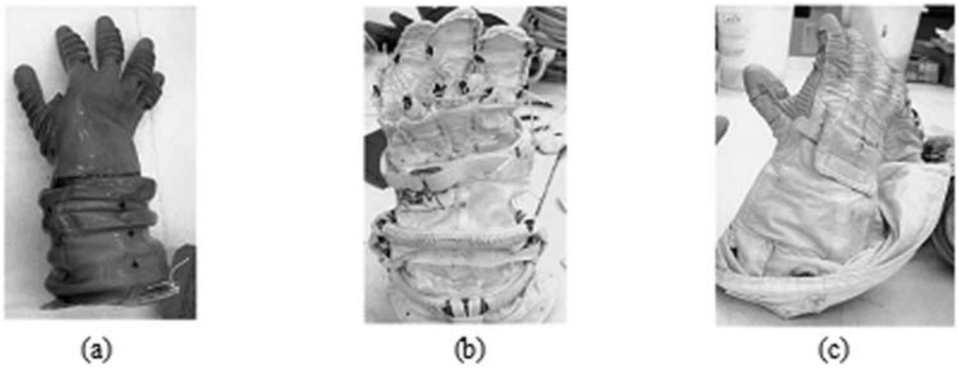

Figure 1. Phase VI glove three layers (a) inner bladder lining; (b) restrainer; (c) outer glove layer.

Administration (OSHA) has created a specific occupational hand protection standard to reduce the occurrence of highly prevalent hand and/or finger injuries. This standard states that:

> Employers shall select and require employees to use appropriate hand protection when employees' hands are exposed to hazards such as those from skin absorption of harmful substances; severe cuts or lacerations; severe abrasions; punctures; chemical burns; thermal burns; and harmful temperature extremes (OSHA 1996).

Accordingly, employers have implemented the usage of a variety of gloves for hand protection. These gloves can be used for the purpose of general protection or designed to mitigate a particular hazard (Riley and Cochran 1988).

Great variation exists in the design and materials of different occupational gloves. This variation is evident in the occupational gloves used by U.S. astronauts during extra vehicular activity (EVA). EVA involves any activity performed outside the spacecraft. These EVA gloves are designed to protect the astronaut's hands from the specific hazards of the extreme occupational conditions. Due to these specific hazards the EVA gloves are designed with three different layers, each with its own purpose in the overall goal of protecting the astronaut (Bishu and Muralidhar 1999) (Figure 1). These spacesuit gloves are very different than aluminised occupational safety gloves, which are used to protect individuals, such as firefighters, against the hazards of extreme radiant heat and flames (Chou et al. 2011) (Figure 2). These gloves address very different hazards but apply to the same overall goal of providing hand protection to the worker and prevent occupational hand injuries.

Although the usage of occupational safety gloves is suggested frequently and is warranted, this usage can sometimes result in negative or unintended issues and injuries. These issues vary greatly and affect many industries in different ways ranging from performance to safety (Dianat, Haslegrave, and Stedmon 2012). Performance issues can be related to productivity in terms of reduction in tactility, dexterity, gripping strength and other measures of physical performance. Safety issues can be related to occupational injury in terms of insufficient protection, skin reactions and occupational glove-hand injuries.

Figure 2. Aluminised occupational safety gloves in occupations such as firefighting.

Occupational glove-hand injuries are widespread among several industries including health care, space, service and manufacturing (Poole 2007; Taylor and Praditsuwan 1996; Viegas et al. 2004; Weistenhöfer et al. 2015; Wulfhorst, Schwanitz, and Bock 2004). These injuries are diverse in conditions present, pathogenesis and severity. In the health care industry the common injuries include glove dermatitis, irritation and allergy (Rose et al. 2009). In the U.S. Space Program, the astronauts experience finger and hand pain, erythema (superficial reddening of the skin) and onycholysis. Index and middle fingers experience pain and erythema more often than other fingers. Pain and erythema also affect finger crotches between the ring and little fingers and between the thumbs and index fingers. Onycholysis is a condition where the victim's nail separates from the nail bed and is often accompanied by the physiological response of discomfort or pain. The astronauts' middle fingernails have been reported as the most frequently affected fingernails by onycholysis (Charvat et al. 2015). In service and manufacturing industries, the gloves have been known to lead to injuries that involve bruising and devitalisation of the tissues within the hand (Muggleton, Allen, and Chappell 1999). The occlusion effect which creates a microclimate between user's hand and the glove is also one significant cause of irritation and macerated softened skin which may also result in additional issues if the gloves provide poor protection against microbes and chemical injuries (Wulfhorst, Schwanitz, and Bock 2004).

Despite the widespread occurrence of glove-related hand injuries, the causal relationship of such injuries with the use of occupational gloves is not completely understood. These injuries are very different in terms of symptoms and occupational conditions present during onset. However, in most occupations, conditions of temperature and humidity that modify the microclimate within the gloves and the occupational demand of repetitive physical exertions are noted as significant in understanding the mechanism of the glove-hand injuries formation (Charvat et al. 2015; Dianat, Haslegrave, and Stedmon 2012; Muggleton, Allen, and Chappell 1999; Viegas et al. 2004). Several physiological response variables are important when it comes to understanding the pathogenesis of glove-related hand injuries. Among them, the measurements of skin conductance are important as it provides a direct measurement of finger/hand perspiration and moisture (Jones et al. 2008; Viegas et al. 2004; Wulfhorst, Schwanitz, and Bock 2004). In addition, measurements of perceived discomfort have been used in risk characterisation/injury causation studies as it highly correlates with muscular efforts, pain and fatigue (Chowdhury et al. 2013; Troiano et al. 2008). Therefore, in this current study, the effect of factors such as temperature, relative humidity and physical exertion was tested as the microclimate modifying factors and the physiological response of the hand–finger system was measured using skin conductance and perceived discomfort.

Approach

A laboratory-based experimental study involving human participants was completed. A custom built microclimate chamber was used to isolate and expose the participant's dominant hand to different occupational conditions of temperature, relative humidity and physical exertion. The physiological response of the hand–finger system was measured using a skin conductance sensor and recordings of participants' perceived discomfort levels.

Participants

A total of nine male participants were recruited for the current research. Participants were excluded from the research if they suffered from any type of musculoskeletal, degenerative or neurological disorder or if they had a history of hand or fingertip pain or any current pain. Most of the participants were university students with no experience of using occupational gloves. Mean (SD) age, height and weight of the participants were 21.3 (2.8) years, 170.2 (10.7) cm and 72.1 (17.9) kg, respectively.

Custom built atmospheric chamber

A 8ft^3 microclimate chamber was custom built using acrylic (Figure 3). The chamber was assembled similar to a cube and the sides were bonded together with a chemical agent. The chamber contained a heater, a humidifier and sensors to measure and control precise levels of temperature and relative humidity. One side of the chamber was fitted with a waterproof medical cast cover that allowed the participants to place their hand within the chamber. This allows for an air tight seal around the participant's wrist, and provides additional control over the atmospheric conditions within the chamber. A few smaller openings were added to the chamber to allow entry for the temperature control device's probe and electrical wire that supplied power to the inside of the chamber for all necessary devices. These holes were purposely designed to be as small as possible to reduce potential loss of control over atmospheric conditions. The base of the chamber was placed on an elevated platform with bath towels for flooring. The bath towels were chosen due to their insulating and form-fitting properties. The base of the chamber was raised to approximately hip height to allow comfortable access for the participants.

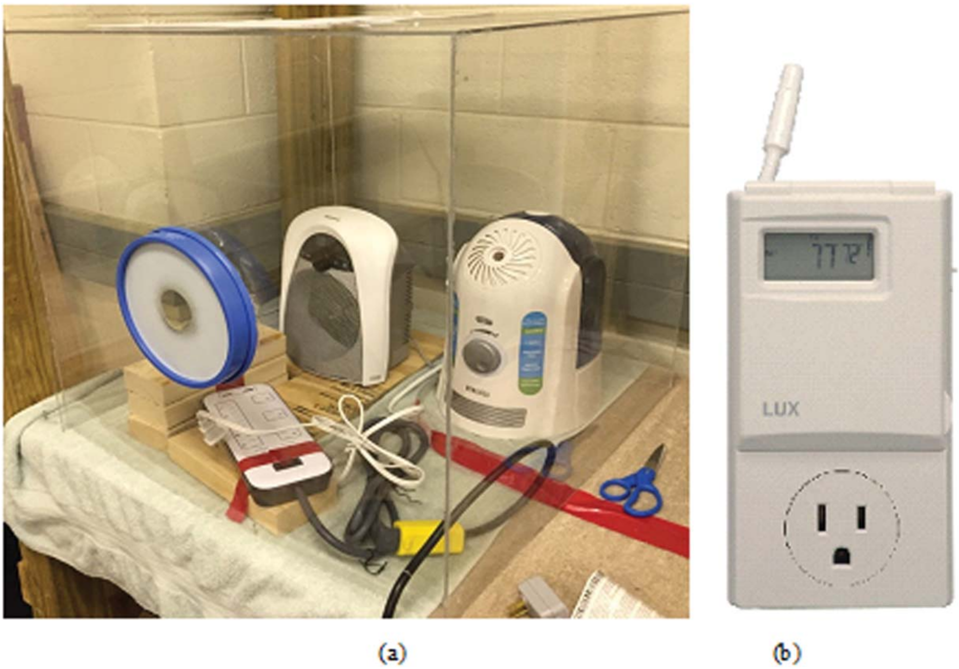

Figure 3. Picture of a custom built microclimate chamber.

Skin conductance sensor

The skin conductance data was collected through a non-invasive, two probe, skin conductance sensor (SA9309M, ThoughtTechnology, Quebec, Canada). The probes were mounted on the medial phalanges of index and ring fingers such that the sensor made contact with palmar skin (Figure 4(a)). The sensors in the probe measure and track skin conductance data in real time; units are micro Siemens (μS). This data was transmitted through the signal isolator (T9405AM, ThoughtTechnology, Quebec, Canada) (Figure 4(b)) allowing the skin conductance sensor to be interfaced with a TeleMyo 2400R G2 receiver (Noraxon USA Inc., Scottsdale, AZ, USA). The MyoResearch XP analysis software (Noraxon USA

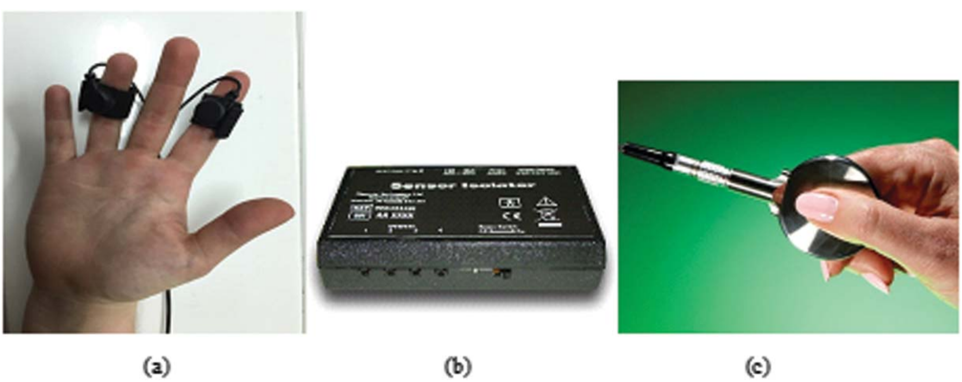

Figure 4. Physiological response measuring equipment: (a) two probe skin conductance sensor with finger straps, (b) signal isolator and (c) pinch meter.

Inc., Scottsdale, AZ, USA) was used to collect, organise and analyse the recorded data. The skin conductance or skin moisture data was collected from very consistent locations of the participants' dominant hand. In addition, the right upper extremity posture was also consistently controlled during measurements such that wrist was supinated 90° with a neutral ulnar/radial deviation; elbow and shoulder flexion was maintained at 70°–90° and 10°–20°, respectively.

Pinch meter

The pinching exertion force data, which was generated by the participants, was obtained with a pinch meter (P200, Biometrics, Newport, United Kingdom) (Figure 4(c)). The pinch meter was directly wired to the wireless TeleMyo 2400R G2 transmitter (Noraxon USA Inc., Scottsdale, AZ, USA) that forwarded the data to the TeleMyo 2400R G2 receiver (Noraxon USA Inc., Scottsdale, AZ, USA). The MyoResearch XP analysis software (Noraxon USA Inc., Scottsdale, AZ, USA) was used to collect, organise and analyse the data. The participants performed lateral pinching using the pinch meter.

Experimental design

A three-factor experimental design was used in this research. Factor 1, pinching exertion, was treated at two levels: (1) exertion and (2) no exertion. Factor 2, temperature, was treated at two levels: (1) 65–75 °F and (2) 85–95 °F. Factor 3, relative humidity, was treated at two levels: (1) 35%–45% relative humidity and (2) 55%–65% relative humidity. These ranges were selected due to two reasons: (1) we were only able to strictly control these ranges with our chamber; (2) the higher ends of the ranges approximately represent the environment within EVA gloves (Amick et al. 2016; Reid and McFarland 2015) and these ranges are at least 10 points apart.

In total, 16 experimental trials (2 levels of physical exertion × 2 levels of relative humidity × 2 levels of temperature × 2 repetitions) were collected from each individual participant. Each trial was five minutes long. The exertion trials always began with a 30-second interval of rest, which was immediately followed by 30-second intervals of lateral pinching at 50% of the participant's maximum strength. Thus, lateral pinching was completed five times (30-second intervals) per exertion trial. During the no exertion trial, the participants simply placed their dominant hand in the chamber at different atmospheric conditions. The experiment was approximately three hours in total duration per participant. The trial order was completely randomised for the factor levels of relative humidity and physical exertion. The trial order of the factor levels of temperature were controlled with the first set of eight trials being held to the lower range of 65–75 °F and the second set of eight trials being held to the higher range of 85–95 °F. A rest period of approximately two to three minutes was provided between each trial to mitigate any effects from fatigue.

Experimental procedure

Upon arriving at the laboratory, the participant was given a thorough explanation of the equipment, data collection procedures and experimental tasks. If the participant decided

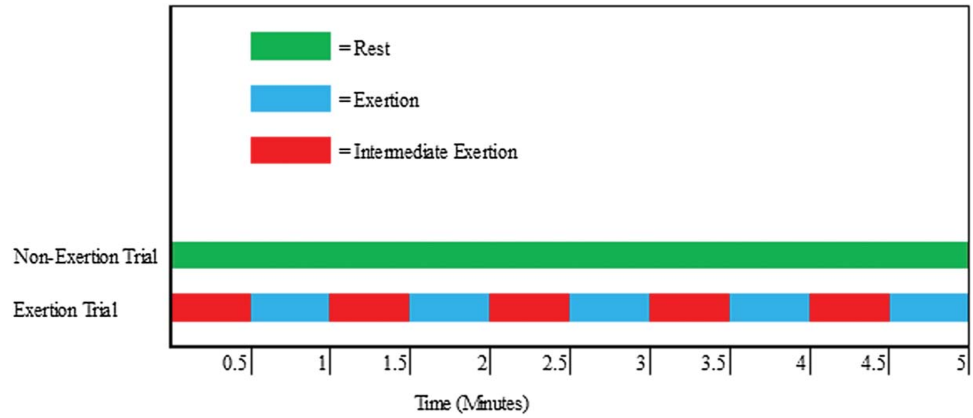

Figure 5. Timeline of exertion and non-exertion trials.

to participate in the study then his signature was obtained on a consent form approved by the local Institutional Review Board. The participant was then trained on performing a lateral pinch exertion using the pinch meter and asked to perform maximum force exertion trials. Three trials of maximum force were collected. In the cases where variability was >10% between trials, a fourth trial was performed and the average of the best three values was used to determine the pinching strength of the participant, and 50% of this value was used for the experimental trials.

A bio-feedback system that allowed the participants to view real-time physical exertion force was used. The participant was given several opportunities to practice maintaining the target force. After the participant demonstrated proficiency in performing the correct level of force, an initial moisture reading was collected from the participant. Then, isopropyl alcohol was applied to the hand–finger system to control the baseline moisture readings. The baseline moisture reading was collected 30 seconds after this application. After these two initial moisture readings, the participant was ready to begin the experimental trials.

Depending on the type of trial, the participant then placed his dominant hand within the chamber and either exerted force or rested (Figure 5). The participant kept his hand in the chamber continuously until the five-minute trial was finished. Immediately at the end of each trial and as soon as possible, a moisture reading was recorded to reduce air exposure. During each of these collections the skin conductance sensor collected data for an interval of 10 seconds. This methodology was chosen due to its implementation in a previous study (Jones et al. 2008). After each trial, the participants were asked to numerically rate their perceived discomfort using Borg's CR-10 scale (Borg 1990). The Borg CR-10 scale contains two columns, one for subjective categories ranging from 'nothing at all' to 'extremely strong' and the other for numerical ranging on a scale of 0–10, '0' indicating 'no discomfort' and '10' indicating 'unbearable discomfort.' After the moisture reading, isopropyl alcohol was then applied to the hand–finger system. Thirty seconds after the application of the isopropyl alcohol, an additional moisture reading was then collected. The participant was then ready for the next trial. These steps were repeated until all 16 trials were completed.

Table 1. Main effects of temperature, humidity and exertion on normalised skin conductance.

Variable			*P*-Value
Temperature	**65–75 °F**	**85–95 °F**	
	−0.077(0.279)	0.052(0.347)	<**0.001**
Humidity	**35%–45%**	**55%–65%**	
	−0.051(0.331)	0.027(0.307)	**0.029**
Exertion	Exertion	No exertion	
	0.127(0.265)	−0.154(0.312)	<**0.001**

Data analysis

General Linear ANOVA models were used for statistical analysis of the skin conductance and perceived discomfort data. Temperature, relative humidity and physical exertion factor levels were treated as fixed factors. The participants were treated as a random blocking factor. Skin conductance data and perceived discomfort data were all treated as dependent variables. The effects of the independent variables on the dependent variables were treated at a significance level of 95%. Minitab 16 software (Minitab Inc., State College, PA, USA) was used to perform the statistical analysis.

The skin conductance data was processed by obtaining a mean over 10-second window for each trial. The mean skin conductance and perceived discomfort data did not follow a normal distribution. Therefore, the data sets were normalised using the following equations:

$$\text{Normalised Skin Conductance} = \frac{\textit{Skin conductance} - \text{Baseline value}}{\text{Maximum skin conductance}}$$

$$\text{Normalised Discomfort} = \frac{\textit{Reported discomfort of trial}}{\text{Maximum reported discomfort of participant}}$$

For the normalised data, the ANOVA assumptions of normality of the data and equality of variance were verified using the Anderson–Darling normality test and Levene's test, respectively.

Results

The main effect of temperature on skin conductance was statistically significant ($P < 0.001$) (Table 1). There was a significant increase in skin conductance during trials of the higher temperature range of 85–95 °F when compared to trials of the lower temperature range of 65–75 °F. The main effect of the relative humidity on skin conductance was statistically significant ($P < 0.001$). There was a significant increase in skin conductance during trials of the higher relative humidity range of 55%–65% when compared to the skin conductance present at the lower relative humidity range of 35%–45%. The main effect of the physical exertion on skin conductance was statistically significant ($P < 0.001$). There was a significant increase in skin conductance during trials where physical exertion was present when compared to trials involving no exertion. All interaction effects were statistically insignificant (Figure 6).

The main effects of temperature and exertion on perceived discomfort were statistically significant (all P-values < 0.001) (Table 2). The perceived discomfort significantly

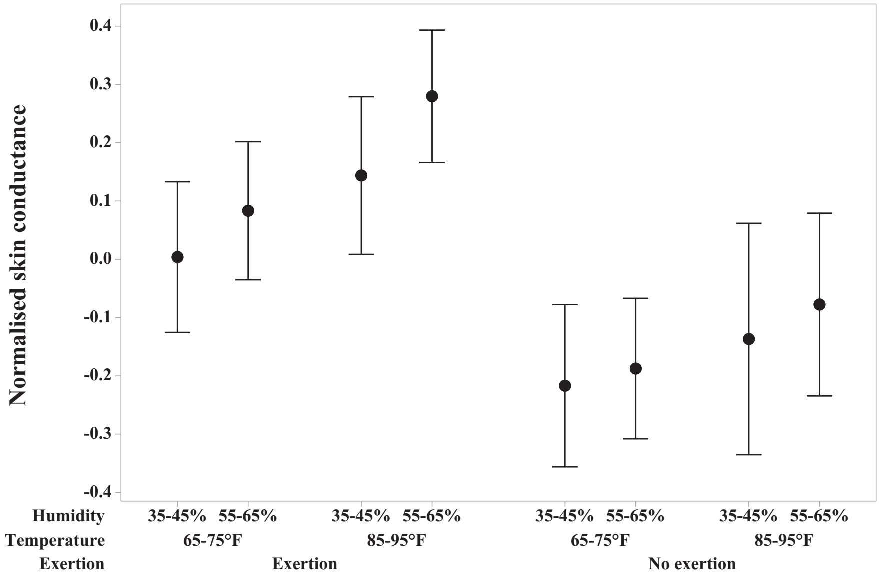

Figure 6. A plot of mean normalised skin conductance at different conditions of humidity, temperature and exertions. The error bars represent 95% confidence interval.

increased with the increase in the temperature and it was significantly higher for physical exertion trials compared to no exertion trials. The interaction effect of temperature and exertion on perceived discomfort was also statistically significant ($P = 0.044$). At the higher temperature range of 85–95 °F, the increase in the perceived discomfort was almost 1.5 times that of increase in the perceived discomfort at the lower temperature range of 65–75 °F. The main effect of the relative humidity and the other interaction effects were statistically insignificant (Figure 7).

Discussion

This study provides baseline physiological response data of the hand–finger system when subjected to controlled conditions of temperature, relative humidity and physical exertions. This data can provide important insight for the injuries to the workers who use gloves for extended periods of time in warm environments that also require repetitive physical exertions.

Table 2. Main effects of temperature, humidity and exertion on normalised perceived discomfort.

Variable			*P*-Value
Temperature	**65–75 °F**	**85–95 °F**	
	0.376(0.235)	0.630(0.299)	<**0.001**
Humidity	**35%–45%**	**55%–65%**	
	0.486(0.290)	0.524(0.305)	**0.306**
Exertion	Exertion	No exertion	
	0.666(0.266)	0.343(0.233)	<**0.001**

Note: Range of normalised perceived discomfort = 0.167 to 1.

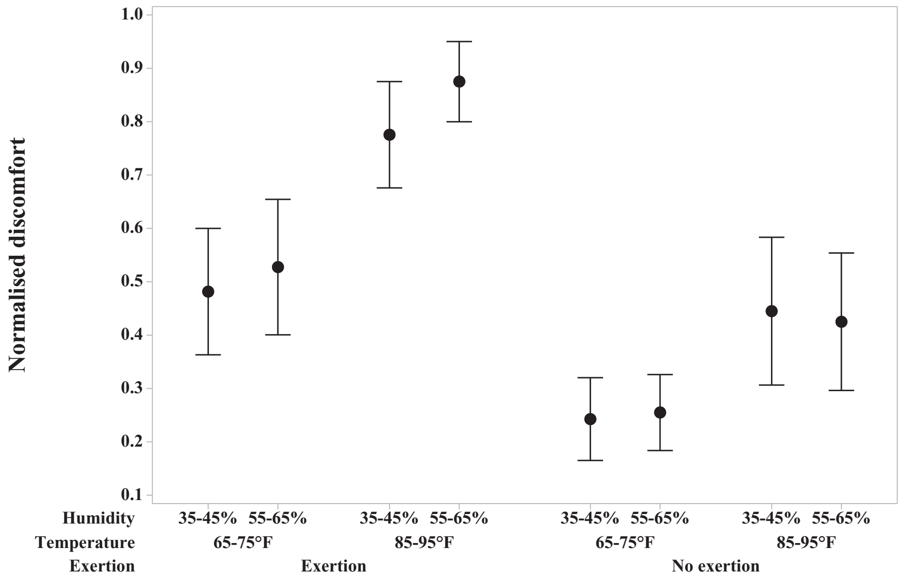

Figure 7. A plot of mean normalised discomfort at different conditions of humidity, temperature and exertions. The error bars represent 95% confidence interval.

The results of this study indicate that the physical exertion, temperature and relative humidity have significant effect on skin conductance. This is in agreement with the findings of previous studies (Charvat et al. 2015; Jones et al. 2008; Lynde 2008; Reid and McFarland 2015; Tsai and Maibach 1999). The physical exertion was found to have a more pronounced effect on the skin conductance compared to temperature and humidity. For the trials with physical exertion, the skin conductance was 210% higher than trials with no physical exertion. Temperature and humidity effects were 165% and 153%, respectively. Typically, the hand and the glove microclimate are warmer and more humid than the ambient environment. The metabolic heat produced during the physical exertions further modifies the microclimate. Production of sweat and its evaporation is critical to maintain thermal equilibrium of this microclimate. However, a lack of cooling mechanisms, which is typically the case inside most of the occupational gloves in general and especially the spacesuit gloves, defeats the body's initial response of sweating to maintain the thermal equilibrium, creating increased sweating. Thus, for physical exertion performed at higher temperature and humidity levels a much increased skin conductance was observed in this study.

If the thermal equilibrium is not maintained within the gloves then long-term use of them can be detrimental to the health of hands, especially the fingers. Onycholysis, observed among U.S astronauts, is one example of such detrimental health effects. Previous studies have linked repetitive hand exertions performed using EVA gloves with the causation of onycholysis. A few researchers have hypothesised that accumulation of moisture on the skin and fingernails in a high relative humidity environment could be one of the causative factors of onycholysis (Jones et al. 2008; Reid and McFarland 2015). The results from this study indicate increased skin conductance/moisture levels for exertions performed at the elevated temperature and humidity levels and thus support this hypothesis. A difference observed in the onycholysis occurrence rates between Phase VI and other EVA gloves also further supports this hypothesis. Onycholysis has increased in prevalence with the implementation of the Phase VI gloves in comparison with other EVA gloves. The Phase VI gloves compared to previous glove versions have a reduction in the liquid cooling ventilation garments vent tube length from the wrist to upper arm, which could have increased levels of relative humidity within the glove.

The perceived discomfort was also affected by the change in the microclimate surrounding the hand–finger system. It has been previously theorised that temperature and physical exertion are directly related to perceived discomfort. This study's results of perceived discomfort data align with this idea. This study's results of perceived discomfort data also agree with the idea that higher temperature would further pronounce the effect of physical exertion on the physical response of discomfort (Armada-da-Silva, Woods, and Jones 2004; Glass, Knowlton, and Becque 1994). The effect of exertion on the perceived discomfort was much higher at the 85–95 °F temperature range compared to 65–75 °F temperature range.

The insignificance of relative humidity in regards to perceived discomfort is in opposition to the findings of several previous studies (Gnaneswaran, Mudhunuri, and Bishu 2008; Jones et al. 2008). One possible cause of the conflicting result of relative humidity being insignificant is that the ranges tested in our study were not very extreme and sufficiently different from these previous studies (Jones et al. 2008). Specifically, much of the literature identified conditions where relative humidity is near 100% and the physiological response of skin conductance or skin moisture is impeded drastically (Bernard and Matheen 1999; Charvat et al. 2015; Jones et al. 2008). An increase in the controlled higher range of relative humidity may result in relative humidity becoming significant in regards to the physiological response of perceived discomfort.

There are several limitations of this study that need to be acknowledged. First, the findings of this study are a function of the experimental conditions investigated. The range of temperature and relative humidity were chosen due to equipment limitations and the physical exertion was limited to lateral pinching. In future studies, the ranges of temperature and relative humidity should be diversified and in more extreme states. An example of an extreme state would be a relative humidity range closer to 100%. Second, participation was voluntary and the participant pool was limited to university-aged students with little to no experience with occupational gloves and do not precisely match the characteristics of the occupational population. Third, to control the effect of gender, only male participants were recruited.

Disclosure statement

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Notes on contributors

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