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Effect of cooling on static postural balance while wearing firefighter's protective clothing in a hot environment

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Abstract

Objectives.—Postural imbalance can result from hyperthermia-mediated muscular fatigue and is a major factor contributing to injuries from falling. The objective of this study was to investigate the effect of exercise-induced hyperthermia and the impact of cooling on postural balance while wearing firefighters' protective clothing (FPC) in a hot environment.

Methods.—A portable force platform measured postural balance characterized by postural sway patterns using center of pressure metrics. Twelve healthy, physically fit males were recruited to stand on the force platform once with eyes open and once with eyes closed before and after treadmill exercise ($40\%\dot{V}O_{2max}$) inside an environmental chamber under hot and humid conditions (30 °C and 70% relative humidity) while wearing FPC. Subjects participated in two randomly assigned experimental phases: control and cooling intervention.

Results.—A significant increase in physiological responses and postural balance metrics was observed after exercising in the heat chamber while wearing FPC. Cooling resulted in a significant effect only on postural sway speed after exercise-induced hyperthermia.

Conclusions.—Hyperthermia can negatively alter postural balance metrics, which may lead to an increased likelihood of falling. The utilization of body cooling reduced the thermal strain but had limited impact on postural balance stability.

Keywords

firefighters; personal protective equipment; postural balance; hyperthermia; heat stress; active cooling

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1. Introduction

Encapsulating firefighters' protective clothing (FPC) may offer protection from both hazardous materials and extreme environmental heat for short periods of time. However, current FPC is heavy, thick, multilayered and bulky, which can affect postural balance during firefighting activities [1,2]. In addition, high levels of work (i.e., increased metabolic heat production) in hot environments while wearing encapsulating FPC is a significant contributor to hyperthermia [3,4]. The American Conference of Governmental and Industrial Hygienists (ACGIH) [5] established the threshold limit value (TLV) guidelines to ensure that core body temperature (T_c) does not exceed a lower threshold safe limit of hyperthermia (38 °C) for extended periods of work while wearing personal protective equipment (PPE). In addition, the guidelines of the National Fire Protection Association (NFPA) Standard 1584 [6] recommend that firefighters' T_c should be maintained within the range 36–38 °C.

Firefighting is usually associated with physically demanding tasks leading to increased fatigue, which may result in postural balance instability [1,2]. Moreover, the increase in T_c approaching the lower threshold safe limit of hyperthermia could be one of the factors affecting postural balance stability, possibly leading to slips, trips and falls. This could potentially result in an injury or fatality [7–9]. The role of fatigue as a contributor to alterations in balance and subsequent increases in falls is further explained by Pau et al. [10], who noted that postural balance among firefighters is greatly affected by the level of fatigue. It has also been suggested that extrinsic factors, such as reduced visibility and heat stress, can result in an elevated risk of slips and falls [10–12]. The increasing risk of physical injuries such as slips and falls is also related to exposure to extended periods of high heat, which may cause heat exhaustion that has been associated with an increase the chance of slips and falls [13]. Finally, it has been reported that wearing FPC alone can negatively affect postural balance in firefighters [14–16].

From a physiological standpoint, the literature suggests that reliance on the natural mechanisms of body cooling alone while wearing personal protective clothing will be insufficient for reducing heat strain [1,7]. The encapsulating nature of the FPC can defeat the normal heat transfer mechanisms of the body, especially sweat vaporization [1,7]. Thus, an external cooling method could help to reduce heat stress severity and associated incidents such as slips and falls. Several studies have evaluated the effectiveness of cooling strategies in the management of the adverse effects of heat stress on firefighters' physiological responses [3,17]. It is evident that continuous cooling provides a potential option through which the physiological function of firefighters can be improved [3,17].

A study conducted by Kim et al. [18] suggested that a continuous cooling method via a wearable liquid cooling garment (LCG) underneath the FPC is an effective method to reduce physiological strain, enhance recovery and extend exercise performance in subsequent sessions of exercise.

However, there is a scarcity of data in the literature on the effect of continuous cooling on the firefighter's motor control, including postural balance. Hence, the objectives of this study were to investigate the effect of hyperthermia, induced by exercise in a hot environment while wearing FPC, and the impact of a continuous cooling method on static postural balance metrics in human subjects. We hypothesized that continuous cooling would limit hyperthermia and help maintain the normal characteristics of postural balance after exercise in a hot environment.

2. Methods

2.1. Study design

The data presented in this study are a subset of a larger research study, portions of which have been published previously and in which some of the following methods have been described in detail [19,20]. Briefly, this study utilized a randomized cross-over design consisting of two experimental phases scheduled on two different days per each subject – control phase (no cooling) and intervention phase (cooling application) – to investigate the effect of cooling application on static postural balance metrics after exercise while wearing FPC in a warm (30 °C) and humid (70% relative humidity [RH]) environment. The study was approved by the National Institute for Occupational Safety and Health (NIOSH) Institutional Review Board (15 NPPTL-01).

2.2. Study population

Twelve healthy, non-smoking, physically fit $\left(\dot{V}O_{2max} \geq 45 ml \cdot kg^{-1} \cdot min^{-1}\right)$ men aged 21–40 years were recruited from the general population to participate in this study. Inclusion criteria for this study have been described elsewhere [19]. Briefly the subjects, in addition to being generally healthy, were not taking any medications (e.g., alcohol, prescription medications, over-the-counter remedies including herbal-based remedies or drugs of abuse) that might interfere with the safe conduct of the study or with the quality of the data collection. The subjects were also required to be physically and mentally capable of completing the tasks required by the study. Each subject served as their own control.

2.3. Medical screening/evaluation

Upon first arrival, oral and written informed consent was obtained from each subject after an orientation about the nature of the study procedures, including potential risks associated with participation. Subjects then completed a medical history questionnaire prior to participation and before each phase of the study as previously described [19].

2.4. Physical fitness evaluation

Subject enrollment and screening procedures have been described elsewhere [19]. Briefly, upon completion of the formal consent process and medical screening, each subject then completed a maximal graded exercise test (GXT) during which aerobic capacity $\left(\dot{V}O_2\right)$, cardiac rhythm (electrocardiogram [ECG]), heart rate (HR), blood pressure (BP) and subjective ratings of perceived exertion (Borg scale) were obtained. The $\dot{V}O_{2max}$ and HR_{max} measures were used to calculate individual subjects' relative exercise intensity (workload) during the experimental phases. In addition, relative workload, set at 40% $\dot{V}O_{2max}$ for the experimental conditions, was calculated after adding the weight of the FPC (20.45 kg) to each subject's measured body weight to account for additional external stress of carrying the FPC load [19].

2.5. Experimental phases

Subjects were scheduled to come to the laboratory on two separate days (at least 1 week apart to prevent training effects) to participate in both the control and intervention phases as previously described [19]. The continuous cooling method used in the intervention phases was adapted from a previously published protocol by Kim et al. [18]. The experimental phases were conducted inside an environmental chamber (air temperature, 30 °C; RH, 70%). During this time, the subjects entered the chamber while wearing FPC, including the self-contained breathing apparatus (SCBA). The experimental phases included four stages as follows: stage 1, a 15-min stabilization period in which the subjects were seated on a chair inside the chamber during which pre-exercise physiological measures were obtained; stage 2, a 5-min transition stage during which the study staff adjusted the treadmill incline and speed necessary to impose a relative workload equivalent to 40% of the subject's $\dot{V}O_{2max}$ as calculated from the GXT; stage 3, a 40-min treadmill exercise at 40% $\dot{V}O_{2max}$ at the end of which the subjects completed the static postural balance test; stage 4, at the completion of the balance test, the subjects then exited the environmental chamber and were seated at ambient room temperature (T_A) (20 °C, 50% RH) for the recovery phase. The subjects were then instructed to remove the FPC and change into clean clothes. Subjects were monitored and remained in the recovery stage (stage 4) and cool liquids (water or sports drink) were provided (ad libitum) during the recovery stage. Subjects continued to be monitored until their T_c fell below 38 °C and HR decreased to < 100 bpm, indicating that the subject had achieved a physiologically stable state during the recovery stage. Upon achieving a physiologically stable state, the subjects could safely be released from the experimental activities for that day. The sequence of the experimental procedures is shown in Figure 1.

2.5.1. Static postural balance measures—

A portable force platform system (AccuSway Optimized™; AMTI, USA) was used to measure the postural balance metrics (static posturography) of subjects directly prior to the experimental phases (before starting stage 1) and directly after the exercise (end of stage 3). The postural balance test consisted of two trials as follows: eyes open trial while standing on a firm surface (EO); followed by eyes closed trial while standing on a firm surface (EC). Each trial duration lasted 30 s and subjects were seated on a chair between subsequent trials. Because firefighters are often required to work in the dark or under conditions of low visibility due to the presence of heavy smoke, the postural balance test is designed to utilize static postural sway as an indirect assessment of different stressors on the central nervous system (CNS) by assessing the visual, vestibular and somatosensory inputs and their effects on maintaining static postural balance [15,21].

Two study staff were positioned on each side of the subject during the testing to monitor and prevent the subject from falling. Postural balance testing was conducted outside the environmental chamber in a quiet area at T_A (20 °C, 50% RH). Outcome variables of the static postural balance tests were sway speed (SS; centimeters per second), sway area (SA; square centimeters), excursion in the anterior–posterior direction (AP; centimeters) and excursion in the medio-lateral direction (ML; centimeters). The SA is encompassed by movement patterns of $X–Y$ coordinates of center of pressure (CP) movements during postural balance tests. SS is the total sway length traveled by the subjects' CP over time during postural balance tests. The ML and AP are maximum displacements of subject's CP in the ML and AP directions, respectively. Data generated by the force platform were processed using custom software (KineLysis©) to calculate the mean values of all static balance outcome measures.

2.5.2. Physiological measures—The physiological variables obtained in this study have been described in detail elsewhere [19], i.e., HR (beats per minute), T_c (degrees Celsius) and mean skin temperature (T_{sk}; degrees Celsius). The HR was measured using a BioHarness Zephyr™ (BioHarness III; Zephyr Technology Corporation, USA) monitor strapped to each participant's chest. T_c was measured by a silastic-coated rectal probe (4600 precision rectal thermistor; YSI Temperature, USA) connected via wire to LabVIEW (LabView 2014 SP1, 14.0.1.4008, National Instruments, USA), which synchronizes the live data. T_{sk} was measured by thermistors (SQ2020-1F8 skin temperature logger; Grant Instruments Ltd, UK) attached to four skin sites (chest, shoulder, thigh and calf) [22]. Statistical analyses were performed on two time points: pre and post exercise per the experimental phase. The pre-exercise measurement was a 1-min average at the end of the stabilization period (stage 1). The post-exercise measurement was calculated using the last 1-min average of the immediate post-exercise stage (stage 3) prior to recovery.

2.6. Equipment and instrumentation

2.6.1. Experimental protective clothing—FPC (Morning Pride/Total Fire Group [now Honeywell], USA) including SCBA (Scott NXG2 AIRPAK with 45-min rated carbon cylinder; Scott Health & Safety, USA) was used throughout this study. Details of the firefighter ensemble used in this study have been published elsewhere [23].

2.6.2. Environmental chamber—A walk-in environmental chamber (WM-Series; Russells Technical Products, USA) was used to create the environmental conditions specified by the study protocol (30 °C, RH 70%) maintained within a range of ±2 °C and ±5% RH.

2.6.3. Liquid cooling garment—A shortened cooling garment [18] was used in this study for the continuous cooling application. Details of the LCG have been described previously [18,19]. Briefly, the LCG (Figure 2) was designed such that it selectively cools specific regions of the body with higher heat exchange capabilities [24]. The garment employs flexible silastic tubing embedded into the inner surface of the fabric which is in direct contact with the skin for heat exchange [18,24]. Cooled water (18 °C) supplied by an external water electric circulator, capable of maintaining constant water temperatures, was circulated through the silastic tubing. Body surface areas covered by the garment tubing were the head, forearm, torso and thigh area. The subjects wore the LCG underneath the FPC in both phases: control (no cooling) and intervention (cooling). The water circulator was connected to the LCG only during intervention phases. Therefore, the only difference between the control and the intervention was whether the cool (18 °C) water was circulated through the LCG providing the cooling effect. There was no cooling effect when the 18 °C water was not circulating through the LCG [18].

2.6.4. Force platform—

An AMTI force plate (AccuSway Optimized™; AMTI, USA) was used for static postural balance measurements. The force plate captured six channels of data: three mutually orthogonal forces and three mutually orthogonal moments. During the postural balance test, these six channels were used for monitoring the movement of coordinates of the CP on the horizontal $X–Y$ plane as per the equations outlined in a previous study involving a postural balance test [25].

2.7. Statistical analysis

All statistical analyses were conducted using R version 3.3.2. Descriptive statistics were computed for T_c and postural balance outcome measures. A two-way analysis of variance (ANOVA) with three levels (time of heat exposure [pre vs post] × cooling application [no cooling vs cooling] × vision condition [EO vs EC]) was conducted to analyze the effect of hyperthermia and the interaction of cooling intervention on postural balance metrics in addition to the effect of vision. An α value of $p \le 0.05$ was considered statistically significant for all comparisons.

Results

The statistical summary (mean ± standard deviation) of subjects' demographic factors is as follows: age 24 ± 3.2 years, height 178 ± 8.7 cm, weight 78.06 ± 8.16 kg, body mass index (BMI) 24.83 ± 3 and maximal oxygen consumption $\left(\dot{V}O_{2\max}\right)$ 56.33 ± 7.42 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$.

3.1. Physiological outcomes

Table 1 presents the changes of physiological responses (T_c) (mean ± standard deviation) used in both phases: control (no cooling) and intervention (cooling).

3.2. Static postural balance outcomes

Table 2 presents the results of static postural balance measures as descriptive statistics (mean ± standard deviation) used in both phases: control (no cooling) and intervention (cooling).

Table 3 presents the simple effect of hyperthermia on static postural balance measures derived from ANOVA. Analysis of the simple main effects of time showed a significant increase in all postural balance metrics (SS, SA, AP, ML) across time, independent of the vision condition (EO, EC) or cooling condition (cooling, no cooling).

Table 4 presents results of the ANOVA of final postural balance values performed on the postural balance metrics as a function of elevation/range and time spent exercising inside the environmental chamber in two phases (control [no cooling], intervention [cooling]) across both vision conditions (EO, EC). There was a statistically significant three-way interaction between the effect of hyperthermia induced by time spent in the heat chamber and cooling intervention on only a postural balance variable (SS) across both vision conditions.

Table 5 presents a results summary of vision effect on postural balance metrics. The simple main effects of vision show that vision has a significant role on the subjects' postural balance metrics (SS, SA, ML) as a function of time spent exercising in the hot chamber (pre, post), independent of the cooling condition but not the AP.

4. Discussion

This study investigated the effect of continuous cooling on static postural balance stability. Hyperthermia was induced by exercise in a hot and humid environment while wearing FPC as described elsewhere [19]. The central hypothesis of this study was that the application of continuous cooling will improve static postural balance stability after exercise in a hot environment while wearing FPC. The effect of demographic factors is negligible since the study utilized young (within the same age group), healthy, male subjects of which several demonstrated an athletic body type with a higher percentage of muscle mass.

4.1. Static postural balance outcomes

The present findings support the study hypothesis, as well as other similar studies, in terms of the effect of hyperthermia on postural stability measures. It has been reported [26] that the combined effect of physical stress in a hot environment while wearing FPC significantly increased CP excursion (AP, ML) and speed (SS) for young, healthy individuals. A significant increase in all static postural balance metrics (SS, SA, AP, ML) in both vision conditions (EO, EC) and cooling conditions (cooling, no cooling) has occurred in subjects who reached the lower safe limit of hyperthermia induced by exercise ($40\%\dot{V}O_{2max}$) while wearing FPC in a warm and humid (30 °C; 70% RH) environment. The vision conditions significantly affected all static postural balance metrics (SS, SA, ML) except for the AP. These findings suggest that in the EC condition where vision is absent, the compensatory feedback from the remaining afferents (proprioceptors and vestibular systems) for postural balance maintenance in hot environments is compromised [27]. The literature suggests that there are functional differences and complementary roles for central and peripheral vision in postural control [26,28–31]. Peripheral vision is predominant in the AP postural control, while central vision is predominant for ML control [26,28–31] and the ML direction requires more control to maintain balance [32,33]. This could explain the limited impact of vision on AP excursion.

In a clinical study, the SA response suggests a role for the vestibular afferent system in maintaining postural balance[34]. Alternatively, an increase in sway length (highly correlated to SS) implies increased postural muscle contractions under the control of proprioceptive afferents. A study by Seliga et al. [35] showed that muscle fatigue during exercise even at room temperature reduced static postural balance control, suggesting a proprioceptive fatigue-mediated influence on postural muscle contractions involved in the maintenance of upright balance.

The present study findings partially support the study hypothesis in terms of the continuous cooling impact on the individual's static postural balance. There was an influence of the cooling method on mitigating SS only. As mentioned earlier, there are limited data in the literature on the effect of cooling application on the firefighter's postural balance stability.

The features of the cooling methods (water temperature, vest materials, tubing size, etc.) used in this study have been demonstrated to be an effective cooling method for stabilizing the physiological responses to heat stress [18,20], but nevertheless have limited effect on postural balance outcomes.

4.2. Study limitations

There were three main limitations of this study: testing conditions, study sample population and cooling parameters. The study was conducted using controlled conditions in an environmental chamber. The hot and humid environmental conditions were set to simulate the average heat conditions faced by firefighters under non-live burn conditions in subtropical or tropical regions. However, firefighters face far more extreme conditions during actual live fire conditions [36] than those in this study. Therefore, the study findings should be used with caution when extrapolating the responses from this study to a live fire scenario. The study also imposed a hot environment exposure for 40 min, which may not represent actual exposure times (~20 min) during firefighting. However, the study did simulate the longest bouts that firefighters typically might experience during firefighting. The study subjects were recruited from the general population with strict health and physical fitness criteria due to the difficulty in recruiting professional firefighters. The study sample population only represents a young and healthy firefighting population excluding unhealthy or older members of the population. Thus, the data are probably not generalizable to the older or less healthy members of the fire service. Finally, the cooling method employed in this study (i.e., water temperature and vest and tube materials) might be limited in its ability to provide completely beneficial effects to motor function (i.e., postural balance). A more powerful cooling application (i.e., lower water temperature) might be needed to achieve a maximal benefit from cooling.

5. Conclusion

The study results suggest that exercising in a warm and humid environment combined with the additional burden from encapsulating FPC can result in significant decrements in postural balance stability. However, the cooling method used in this study appears to result in a limited improvement of static postural balance stability – specifically SS. This could be due to the parameters (water temperature, tubing size) of the cooling method. In addition, visual conditions significantly affected all static postural balance metrics (SS, SA, ML) except the AP. These findings suggest that where vision is absent, either with the eyes closed or in an environment of limited visibility (e.g., a smoke-filled or dark room), the compensatory feedback from the remaining non-visual afferents (proprioceptors and vestibular systems) for postural balance maintenance in hot environments is compromised. It is possible that these effects were due to the selected water temperature, duration of heat exposure, hydration status or other factors. Further investigation into the mitigating effect of BMI, age and gender, as well as the cooling method used, is certainly warranted.

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References

[1]. White SC, Hostler D. The effect of firefighter protective garments, self-contained breathing apparatus, and exertion in the heat on postural sway. Ergonomics. 2017;60(8):1137–1145. Doi:10.1080/00140139.2016.1257162 [PubMed: 27822982]

[2]. Colburn D, Russo L, Burkard R, et al. Firefighter protective clothing and self-contained breathing apparatus does not alter balance testing using a standard sensory organization test or motor control test in healthy, rested individuals. Appl Ergon. 2019;80:187–192. Doi:10.1016/j.apergo.2019.05.010 [PubMed: 31280804]

[3]. Hostler D, Reis SE, Bednez JC, et al. Comparison of active cooling devices with passive cooling for rehabilitation of firefighters performing exercise in thermal protective clothing: a report from the Fireground Rehab Evaluation (FIRE) trial. Prehosp Emerg Care. 2010;14:300–309. Doi:10.3109/10903121003770654 [PubMed: 20397868]

[4]. Smith DL, Petruzzello SJ, Goldstein E, et al. Effect of live-fire training drills on firefighters' platelet number and function. Prehosp Emerg Care. 2011;15:233–239. Doi:10.3109/10903127.2010.545477 [PubMed: 21366433]

[5]. ACGIH. 1992–1993 threshold limit values for chemical substances and physical agents and biological exposure indices. Cincinnati (OH): ACIGH Signature; 1992.

[6]. NFPA. Standard on the rehabilitation process for members during emergency operations and training exercises. Quincy (MA): National Fire Protection Association; 2008. Standard NFPA 1584.

[7]. Barr D, Gregson W, Reilly T. The thermal ergonomics of firefighting reviewed. Appl Ergon. 2010;41(1):161–172. Doi:10.1016/j.apergo.2009.07.001 [PubMed: 19664755]

[8]. Mihara M, Miyai I, Hatakenaka M, et al. Role of the prefrontal cortex in human balance control. NeuroImage. 2008;43(2):329–336. Doi:10.1016/j.neuroimage.2008.07.029 [PubMed: 18718542]

[9]. Singh U, Mani A, James K, et al. Effects of heat exposure from live-burn fire training on postural stability of firefighters. Ergon Int J. 2019;3(4):1–20. Doi:10.23880/eoji-16000213

[10]. Pau M, Kim S, Nussbaum MA. Fatigue-induced balance alterations in a group of Italian career and retained firefighters. Int J Ind Ergon. 2014;44(5):615–620. Doi:10.1016/j.ergon.2014.06.010

[11]. Britton C, Lynch CF, Ramirez M, et al. Epidemiology of injuries to wildland firefighters. Am J Emerg Med. 2013;31(2):339–345. Doi:10.1016/j.ajem.2012.08.032 [PubMed: 23158597]

[12]. Kong PW, Suyama J, Hostler D. A review of risk factors of accidental slips: trips, and falls among firefighters. Saf Sci. 2013;60:203–209. Doi:10.1016/j.ssci.2013.07.016

[13]. Hostler D, Horn G. Chapter 21 Slips, Trips, and Falls in the Firefighting Community. In: Hsiao H, editor. Fall prevention and protection: principles, guidelines, and practices. Boca Raton (FL): CRC Press; 2016. p. 369–386.

[14]. Punaxallio A, Lusa S, Luukkonen R. Protective equipment affects balance abilities differently in younger and older firefighters. Aviat Space Environ Med. 2003;74(11):1151–1156. [PubMed: 14620471]

[15]. Sobeih TM, Davis KG, Succop PA, et al. Postural balance changes in on-duty firefighters: effect of gear and long work shifts. J Occup Environ Med. 2006;48(1):68–75. Doi:10.1097/01.jom.0000181756.38010.d2 [PubMed: 16404212]

[16]. Kincl LD, Bhattacharya A, Succop PA, et al. Postural sway measurements: a potential safety monitoring technique for workers wearing personal protective equipment. Appl Occup Environ Hyg. 2002;17(4):256–266. Doi:10.1080/10473220252826565 [PubMed: 11942669]

[17]. Barr D, Gregson W, Reilly T. The thermal ergonomics of firefighting reviewed. Appl Ergon. 2010;41(1):161–172. Doi:10.1016/j.apergo.2009.07.001 [PubMed: 19664755]

[18]. Kim J-H, Coca A, Williams WJ, et al. Effects of liquid cooling garments on recovery and performance time in individuals performing strenuous work wearing a firefighter ensemble. J Occup Environl Hyg. 2011;8(7):409–416. Doi:10.1080/15459624.2011.584840

[19]. Aljaroudi AM, Kadis DS, Bhattacharya A, et al. Effect of continuous cooling on inhibition and attention while wearing firefighter's PPE in a hot environment. J Occup Environ Hyg. 2020;17(5):243–252. Doi:10.1080/15459624.2020.1726933 [PubMed: 32150701]

[20]. Aljaroudi AM, Bhattacharya A, Yorio P, et al. Probability of hyperthermia in a hot environment while wearing a liquid cooling garment underneath firefighters' protective clothing. J Occup Environ Hyg. 2021;18(4–5):203–211. Doi:10.1080/15459624.2021.1898622 [PubMed: 33819135]

[21]. Ivanenko Y, Gurfinkel VS. Human postural control. Front Neurosci. 2018;12:171–179. Doi:10.3389/fnins.2018.00171 [PubMed: 29615859]

[22]. Ramanathan NL. A new weighting system for mean surface temperature of the human body. J Appl Physiol. 1964;19:531–533. Doi:10.1152/jappl.1964.19.3.531 [PubMed: 14173555]

[23]. Williams WJ, Coca A, Roberge R, et al. Physiological responses to wearing a prototype firefighter ensemble with enhanced chemical/biological hazard protection. J. Occup. Environ. Hyg. 2011;8:49–57. Doi:10.1080/15459624.2011.538358 [PubMed: 21154108]

[24]. Koscheyev VS, Coca A, Leon GR, et al. Individual thermal profiles as a basis for comfort improvement in space and other environments. Aviat Space Environ Med. 2002;73(12):1195–1202. [PubMed: 12498548]

[25]. Bhattacharya A, Morgan R, Shukla R, et al. Non-invasive estimation of afferent inputs for postural stability under low levels of alcohol. Ann Biomed Eng. 1987;15(6):533–550. Doi:10.1007/BF02364247 [PubMed: 3688583]

[26]. White SC, Hostler D. The effect of firefighter protective garments, self-contained breathing apparatus, and exertion in the heat on postural sway. Ergonomics. 2017;60(8):1137–1145. Doi:10.1080/00140139.2016.1257162 [PubMed: 27822982]

[27]. Ross JA, Shipp EM, Trueblood AB, et al. Ergonomics and beyond: understanding how chemical and heat exposures and physical exertions at work affect functional ability, injury, and long-term health. Hum Factors. 2016;58(5):777–795. Doi:10.1177/0018720816645457 [PubMed: 27125533]

[28]. Nougier V, Bard C, Fleury M, et al. Contribution of central and peripheral vision to the regulation of stance: developmental aspects. J Exp Child Psychol. 1998;68(3):202–215. Doi:10.1006/jecp.1997.2427 [PubMed: 9514769]

[29]. Stoffregen TA. Flow structure versus retinal location in the optical control of stance. J Exp Psychol Hum Percept Perform. 1985;11(5):554–565. Doi:10.1037/0096-1523.11.5.554 [PubMed: 2932530]

[30]. Stoffregen TA, Schmuckler MA, Gibson EJ. Use of central and peripheral optical flow in stance and locomotion in young walkers. Perception. 1987;16(1):113–119. Doi:10.1068/p160113 [PubMed: 3671034]

[31]. Warren WH, Kurtz KJ. The role of central and peripheral vision in perceiving the direction of self-motion. Percep Psychophys. 1992;51(5):443–454. Doi:10.3758/BF03211640

[32]. Palmisano S, Apthorp D, Seno T, et al. Spontaneous postural sway predicts the strength of smooth vection. Exp Brain Res. 2014;232(4):1185–1191. Doi:10.1007/s00221-014-3835-y [PubMed: 24449012]

[33]. Winter D Human balance and posture control during standing and walking. Gait Posture. 1995;3(4):193–214. Doi:10.1016/0966-6362(96)82849-9

[34]. Yasuda T, Nakagawa T, Inoue H, et al. The role of the labyrinth, proprioception and plantar mechanosensors in the maintenance of an upright posture. Eur Arch Otorhinolaryngol. 1999;256(Suppl. 1):S27–S32. Doi:10.1007/PL00014149 [PubMed: 10337523]

[35]. Seliga R, Bhattacharya A, Succop P, et al. Effect of workload and respirator wear on postural stability, heart rate, and perceived exertion. AIHA J. 1991;52(10):417–422. Doi:10.1080/15298669191364965

[36]. Mani A, Musolin K, James K, et al. Risk factors associated with live fire training: buildup of heat stress and fatigue, recovery, and role of micro-breaks. Occup Ergon. 2013;11(2,3):109–121. Doi:10.3233/OER-130212

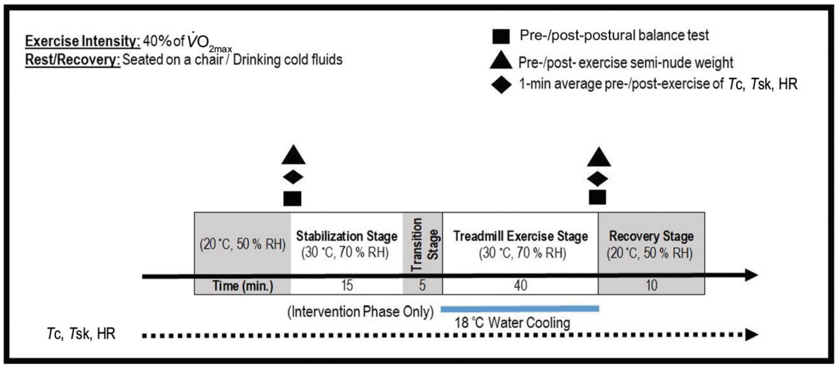

Figure 1.

Sequence of the experimental procedures. Reprinted by permission of Taylor & Francis Ltd (http://www.tandfonline.com) on behalf of JOEH, LLC from Aljaroudi et al. [20]. Note: The full color version of this figure is available online. HR = heart rate (beats per minute); RH = relative humidity (percentage); T_c = core body (rectal) temperature (degrees Celsius); T_{sk} = skin temperature (degrees Celsius); $\dot{V}O_{2,\max}$= maximal oxygen consumption (milliliters per kilogram per minute).

Figure 2.

Subject wearing the liquid cooling garment (LCG) used in the study. Note: Several different views presented. The LCG is designed to cover areas of the body with high heat exchange capacity. The full color version of this figure is available online (National Institute for Occupational Safety and Health [NIOSH] file photograph).

Table 1.

Descriptive summary statistics of physiological responses.

	Control (no cooling)		**Intervention (cooling)**	
Variable (unit)	**Pre**	**Post**	**Pre**	**Post**
HR (beats per minute)	82 ± 13	171 ± 15	91 ± 19	142 ± 25
T_c (degrees Celsius)	36.92 ± 0.27	38.25 ± 0.36	36.89 ± 0.33	37.82 ± 0.48
T_{sk} (degrees Celsius)	34.8 ± 0.5	36.9 ± 0.6	34.2 ± 0.5	35.3 ± 0.5

Note: Data presented as mean ± standard deviation. HR = heart rate; T_C = core body temperature; T_{SK} = mean skin temperature.

Table 2.

Descriptive summary statistics of postural balance metrics.

		Control (no cooling)		Intervention (cooling)	
Variable (unit)	**Vision**	**Pre**	**Post**	**Pre**	**Post**
SS (centimeters per second)	EO	0.78 ± 0.07	0.97 ± 0.16	0.76 ± 0.08	0.85 ± 0.15
	EC	1.02 ± 0.21	1.14 ± 0.25	1.05 ± 0.22	1.10 ± 0.22
SA (square centimeters)	EO	0.84 ± 0.29	1.25 ± 0.65	0.77 ± 0.34	1.09 ± 0.53
	EC	1.00 ± 0.30	1.44 ± 0.49	1.27 ± 0.45	1.66 ± 0.58
AP (centimeters)	EO	0.73 ± 0.41	0.96 ± 0.46	0.86 ± 0.49	1.02 ± 0.58
	EC	0.78 ± 0.32	0.94 ± 0.36	0.77 ± 0.22	1.05 ± 0.41
ML (centimeters)	EO	1.68 ± 0.43	2.10 ± 0.71	1.42 ± 0.38	1.81 ± 0.74
	EC	1.96 ± 0.32	2.44 ± 0.42	2.27 ± 0.49	2.64 ± 0.80

Note: Data presented as mean ± standard deviation. AP = excursion in the anterior–posterior direction; EC = eyes closed trial while standing on a firm surface; EO = eyes open trial while standing on a firm surface; ML = excursion in the medio-lateral direction; SA = sway area; SS = sway speed.

Table 3.

Simple effects of time of hyperthermia on postural balance metrics.

Variable (unit)	***F***	***p***	**η_p^2**
SS (centimeters per second)	9.72	0.01 *	0.47
SA (square centimeters)	12.72	< 0.01 *	0.54
AP (centimeters)	7.82	0.02 *	0.42
ML (centimeters)	13.63	< 0.01 *	0.55

*Significant difference for each of the variables.

Note: AP = excursion in the anterior–posterior direction; ML = excursion in the medio-lateral direction; η_p^2 = partial η^2; SA = sway area; SS = sway speed.

Table 4.

Three-way interaction effects between hyperthermia, cooling intervention and vision on postural balance metrics.

Variable (unit)	***F***	***p***	η_p^2
SS (centimeters per second)	7.15	0.02 *	0.39
SA (square centimeters)	0.69	0.42	0.06
AP (centimeters)	0.06	0.81	0.00
ML (centimeters)	0.12	0.74	0.01

* Significant difference in variable identified.

Note: AP = excursion in the anterior–posterior direction; ML = excursion in the medio-lateral direction; η_p^2 = partial η^2; SA = sway area; SS = sway speed.

Table 5.

Statistical analysis of vision effect on postural balance metrics in both experimental phases (control, intervention).

Variable (unit)	***F***	***p***	η_p^2
SS (centimeters per second)	29.25	$< 0.01^*$	0.73
SA (square centimeters)	38.26	$< 0.01^*$	0.78
AP (centimeters)	0.012	0.92	0.001
ML (centimeters)	23.47	$< 0.01^*$	0.68

[*] Significant difference in the variables identified.

Note: AP = excursion in the anterior–posterior direction; ML = excursion in the medio-lateral direction; η_p^2 = partial η^2; SA = sway area; SS = sway speed.