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Repeatability of physiological responses during two repeated protective clothing performance tests under identical test conditions

W. Jon Williams*, Aitor Coca, Jung-Hyun Kim, Raymond Roberge

National Personal Protective Technology Laboratory (NPPTL/NIOSH/CDC), 626 Cochrans Mill Road, B29-108, Pittsburgh, PA 15236, United States

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ABSTRACT

Physiological variables were measured in subjects ($n = 10$) during exercise (50% $\dot{V}\,O_{2max}$) on two separate occasions while wearing protective clothing under identical controlled conditions (22 °C, 50% relative humidity). We hypothesized that there would be no significant difference in measured physiological variables between two separate trials. Rectal temperature and heart rate responses were not statistically different between trials and within subjects ($p = 0.270$; $p = 0.85$, respectively) whereas mean skin temperature ($p = 0.049$) and sweat rate ([kg•h^{-1}]; 1.31 ± 0.52 vs. 1.17 ± 0.38; $p = 0.438$) showed a greater variability between trials. We concluded that in general, that heart rate and rectal temperature responses during exercise testing while wearing protective clothing are less variable and more repeatable than sweat rate and skin temperature responses.

Relevance to Industry: Comparison of the physiological "burden" of different protective ensembles may aid industry in the proper selection and use of the ensemble that balances both the protective nature against hazards with the least physiological burden to the wearer. Repeatable testing increases the reliability of the selection of the appropriate ensemble.

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1. Introduction

While personal protective clothing (PC) effectively provides the wearer with a barrier against various hazards in a variety of occupational settings, it has also been reported that working while wearing PC imposes a considerable physiological burden to the wearer (Selkirk and McLellan, 2004; Manning and Griggs, 1983). For instance, increased muscular work results in an increase in metabolic heat production resulting in an increase in body temperature. This thermoregulatory burden is characterized by an increase in heart rate (HR), and perceived fatigue leading to reduced duration and efficiency of work (Nunneley, 1989; Kraning and Gonzalez, 1991; McLellan et al., 1993; Kenny et al., 1999).

Common practice in the assessment of the occupational suitability of PC includes measurements of physiological variables such as body temperature (core and skin), cardiovascular indexes (e.g., HR), hydration status, as well as tolerable exposure time or exercise endurance (McLellan et al., 1993; Williams et al., 2011; Selkirk and McLellan, 2004; White and Hodous, 1991; Åstrand, 1960). These physiological variables are measured while the individual wearing PC performs exercise with pre-determined work intensities and under specific environmental conditions. The results obtained from these physiological assessments have been utilized in an effort to compare the thermal characteristics of different PCs (Nunneley, 1989; Montain et al., 1994; Kenny et al., 1999; Barker et al., 2000) or have been used to determine physiological and/or work limits imposed by a specific type of PC (Kraning and Gonzalez, 1991; McLellan et al., 1993; Williams et al., 2011; Selkirk and McLellan, 2004).

The scientific findings from previous investigations, concerning physiological responses to PC under various conditions, have contributed to the development of heat stress mitigation strategies such as work-to-rest ratio, nutrition (e.g., hydration), acclimatization, as well as the development of a standard practice for PC user performance testing (ASTM F-2668, 2007). Nevertheless, a determination of the degree of repeatability of measurements of physiological parameters during separate PC user performance testing

Abbreviations: PC, protective clothing; HR, heart rate; HR_{max}, heart rate measured at peak or maximal exercise; T_{core}, body core temperature; $\dot{V}\,O_2$, rate of oxygen consumption (mL·kg^{-1}·min^{-1} or L·min^{-1}); $\dot{V}\,O_{2max}$, rate of maximal oxygen consumption (mL·kg^{-1}·min^{-1} or L·min^{-1}); $\dot{V}\,CO_2$, rate of carbon dioxide production (mL·kg^{-1}·min^{-1} or L·min$^{-1)}$; GXT, graded exercise test; SpO_2, oxyhemoglobin saturation as measured by a pulse oximeter; BP, blood pressure; T_{rec}, rectal temperature – an accepted index of body core temperature; T_{sk}, skin temperature; RH, relative humidity; SCBA, self contained breathing apparatus; SR, sweat rate.

* Corresponding author. Tel.: +1 412 386 4002; fax: +1 412 386 6864.
E-mail address: aun7@cdc.gov (W.J. Williams).

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trials under identical environmental conditions has rarely, if ever, been established.

To our knowledge, there has been only one study in which core temperature (T_{core}) was repeatedly measured in the same experimental setting during a short period of exercise (18 min). During these experiments, the variability of rectal and esophageal temperature responses to different degrees of clothing insulation was tested (Jette et al., 1995). Unfortunately, due to limitations in time, logistics, and resources, most physiological studies are only conducted once. Therefore, the question arises as to whether the physiological responses to wearing PC under specific conditions will be the same or similar (±5% of each other) when measured during separate repeat trials? Therefore, the purpose of the present study was to determine the degree of repeatability of physiological variables obtained from subjects participating in two separate identically controlled tests. We hypothesized that repeat physiological measurements would provide nearly identical (±5%) results during separate but otherwise identical PC user performance tests.

2. Materials and methods

2.1. Subjects

Ten healthy, non-smoking subjects (7 men and 3women) (mean ± SD) age (yrs.): 25.3 ± 5.9, height (m): 1.74 ± 0.08, weight (kg): 73.1 ± 13.5, body mass index (kg m^{-2}): 24.1 ± 2.9, body surface area (m^2): 1.9 ± 0.2, and maximal oxygen consumption ($\dot{V}O_{2max}$; ml kg^{-1} min^{-1}): 45.2 ± 7.5, were recruited to participate in this study. Three of the subjects were professional firefighters. The remaining subjects were age, gender, and fitness matched to the general population of firefighters under the age of 40 years which was the maximal age we were permitted to test based on National Institute for Occupational Safety and Health (NIOSH) Human Subject Review Board (HSRB) guidelines. Written and oral informed consent was obtained from all subjects prior to study participation. The study protocol was approved by the NIOSH HSRB. All subjects were first screened by a physician at a designated medical clinic for musculoskeletal, cardiovascular, and pulmonary disorders which would exclude them from participation in this study and were taking no medications that might affect their performance (e.g., beta blockers, ephedra-like drugs, etc.). Upon receiving medical clearance, each subject performed a maximal graded exercise test (GXT) to determine peak aerobic capacity as well as for the detection of any undiagnosed cardiovascular disease that would exclude the subject from study participation. The GXT involved being instrumented with a mouth bit for the measurement of oxygen consumption and carbon dioxide production ($\dot{V}O_2$ and $\dot{V}CO_2$, respectively), a pulse oximeter for measurement of oxyhemoglobin saturation (SpO_2), skin electrodes for the measurement of the electrocardiogram (ECG) and skin temperature (T_{sk}), a sphygmomanometer cuff for the auscultative measurement of blood pressure (BP) during exercise, and a flexible rectal thermistor for the measurement of body core (rectal) temperature (T_{rec}). During the GXT, physiological variables were recorded as the treadmill speed and incline were increased each minute until the subject indicated that he/she could not continue with the exercise (volitional fatigue). At that point, the peak $\dot{V}O_2$, $\dot{V}CO_2$, heart rate (HR), blood pressure (BP), T_{sk}, and T_{rec} were recorded and taken to be the response to "maximal" exercise. $\dot{V}O_{2max}$ was considered to be reached when an increase in exercise did result in an increase in $\dot{V}O_2$ and when the respiratory exchange ratio (CO_2 produced/O_2 consumed), was >1.15. The GXT test, as well as all the other repeat testing, was separated by not less than 7 days to prevent aerobic training effects and acclimation to the heat (Williams et al., 2011).

2.2. Experimental procedure and measurements

The subjects completed a laboratory-based PC user performance test protocol while wearing a standard set of structural firefighter PC on two separate occasions (Trial 1 and 2). The PC, as described in detail elsewhere (Williams et al., 2011) consisted of helmet, hood, turnout jacket, pants, gloves, and boots (Morning Pride/Total Fire Group, Dayton, OH). The firefighter ensemble also included a self-contained breathing apparatus (SCBA) (NXG2 Airpak, Scott Health & Safety, Monroe, NC). The total weight of the firefighter PC with SCBA was 19.96 ± 0.38 kg. All subjects were instructed to avoid strenuous exercise, alcohol, caffeine, and any acute exposure to significant environmental (e.g., heat) stress for 24 h prior to their participation in the experimental protocol.

Upon their arrival at the laboratory, and prior to testing, all subjects were medically screened by the laboratory physician to determine their ability to safely participate in the protocol. This consisted of receiving a physical examination and completion of a written medical questionnaire regarding their current health status. Urine samples were collected from each subject to screen for common drugs of abuse (Triage™) and pregnancy testing (for women subjects). The subjects were then taken to an environmental chamber and instrumented with physiological sensors after which the subjects donned the PC and SCBA. The testing protocol consisted of three stages: 1) stabilization (10 min), 2) treadmill exercise to volitional fatigue, and 3) rest in an environmental chamber in which air temperature and relative humidity were maintained at 22 °C and 50% relative humidity (RH) yielding a heat index of 25 °C. During the stabilization stage, the subjects sat in a chair, and consumed a predetermined amount of water (5 mL kg^{-1} body mass) to promote a euhydrated state prior to the test. Baseline T_{rec}, T_{sk}, and HR were obtained during this time. Once baseline measurements were obtained, the subjects participated in a warm-up phase at 30% $\dot{V}O_{2max}$ for 2 min after which they performed a treadmill exercise equal to 50% $\dot{V}O_{2max}$. Individual exercise intensities were calculated from $\dot{V}O_{2max}$ measured during the GXT by adding the weight load of PC and SCBA to the subjects body weight and converting absolute $\dot{V}O_2$ (L min^{-1}) to relative $\dot{V}O_2$ (mL kg^{-1} min^{-1}).

During the exercise stage, the subjects breathed through the SCBA's full face respirator. However, breathing air was supplied to the SCBA mask by a hose connected to external Grade D breathing air (#200 steel cylinder containing an air volume equal to 6 m^3) to avoid emptying the SCBA cylinder and leading to changes in SCBA weight during the trials. The maximum exercise duration was set for 45 min (excluding the warm-up) which was equal to the maximum duration of a 45 min-rated SCBA. The testing was stopped, however, if the subjects reached any of the following test termination criteria: 1) subject request for any reason, 2) ≥90% HR_{max} (>1 min), 3) subject exhibited any symptoms including dizziness, chest pain, nausea, etc., or 4) reached a $T_{rec} \geq 39$ °C. Upon the completion of treadmill exercise, the subjects were seated on a chair for a 5 min rest period. During the rest period, the subjects again consumed a controlled amount of water (5 mL kg^{-1} of body mass), but did not remove either the PC or the SCBA. The subjects repeated the test protocol at the same time each the day to avoid any potential influence of circadian rhythm on their physiological responses (Smolander et al., 1993).

The subject's T_{rec} was measured by a rectal thermistor (4600 precision rectal thermometer, YSI Temperature, Dayton, OH) inserted 13 cm beyond the anal sphincter. T_{sk} was measured using skin thermistors (Grant probe high precision thermistors, type EUS-UU-VL5-0, Grant Instruments Ltd, Cambridgeshire, England) secured by adhesive surgical tape onto four ipsilateral skin sites: upper chest, shoulder, anterior thigh, and calf. Measurements of T_{rec}