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

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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.

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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}

and T_{sk} were recorded continuously through a data acquisition system (SQ2020-1F8 data logger, Grant Instruments Ltd, Cambridgeshire, England) and mean T_{sk} was calculated using modified weighting coefficients (Ramanathan, 1964). HR was monitored using a Polar Heart Rate Monitor (Series 610, Lake Success, NY) on a chest strap. All data were collected continuously throughout the testing and presented as 1 min average values. Pre- and post-test nude body mass was measured by a precision platform scale to the nearest 2 g (GSE electronic scale series 4450, Farmington Hills, MI) with corrections for fluid consumption and loss of body fluid from sweating. PC weight was also recorded pre- and post-test to determine the amount of sweat absorbed into the ensemble material. These measurements assisted in the determination of sweat loss experienced by subjects during the test. The total post-test weight loss measured in subjects was then converted to sweat rate$\cdot$min^{-1} with an adjustment for the total duration of each trial.

2.3. Statistical analysis

Upon completion of the data collection, individual data from trial 1 and 2 were paired and summarized as group means ± standard deviation (SD). Due to the difference in exercise duration completed by each subject between the two trials, T_{rec}, T_{sk}, and HR data were summarized at the following time points: baseline, 5 min, 10 min, 15 min, 20 min, end-exercise, and end-rest. A repeated measures analysis of variance (ANOVA) was used to determine main effects and interactions of each variable across the time points (baseline to 20 min) and trials. The Greenhouse-Geisser correction for assumptions of sphericity and was used to designate significance level, and the least significant difference (LSD) adjustment was chosen for post-hoc pairwise comparison. Therefore, end-exercise and end-rest a paired *t*-test was conducted to compare the dependent variables between trials. For sweat rate, a paired *t*-test analysis was used to compare the sweat rate between trials. All statistical analyses were performed using SPSS 19 and statistical significance was accepted when $p < 0.05$.

3. Results

All subjects completed at least 20 min of exercise in both trials of the PC performance testing protocol and data for each variable were acquired in a paired fashion. One subject was able to complete the entire 45 min exercise protocol without reaching any of the test termination criteria. For all other subjects, exercise testing was terminated due to volitional fatigue, a sustained HR ≥ 90% HR_{max}, or at the request of the subject (Table 1). The group mean exercise duration was not significantly different between Trial 1 and 2 ($p > 0.05$). When individual data were analyzed, it was noted that 4 of 10 subjects showed considerable difference in exercise duration between the trials (ranging from 24 to 35%). Thus, exercise duration (i.e., maximal exercise time while wearing a PC) was repeatable between group means but with a high degree of variability between individual subjects.

The T_{rec}, T_{sk}, and HR responses among group means during the time course of the two trials are depicted in Fig. 1. Baseline T_{rec} was not significantly different (0.12 °C) between Trial 1 and Trial 2. Following the onset of exercise, T_{rec} tended to decrease slightly (~0.01 °C) from baseline until the 5 min point in both trials. After 5 min of exercise, T_{rec} steadily increased at a mean rate of 0.02 °C min^{-1} until the termination of exercise in both trials. Thus, the difference in the T_{rec} responses between the trials remained relatively constant from baseline throughout the entire testing until the completion of the trial. Following exercise, the recovery rate (initial increase followed by a decrease) in T_{rec} was also similar between Trial 1 and 2 (0.18 ± 0.05 and 0.17 ± 0.05, respectively), regardless of T_{rec} level at the end of exercise. Except for the main effect of time on T_{rec} elevation during exercise ($p < 0.001$), T_{rec} response was not different either between trials or within subjects.

Table 1
Individual and group mean data ($n = 10$) for exercise duration in the two trials.

Subjects	Exercise duration completed (min)		Difference between trials	
	Trial 1	Trial 2	Min	%
A	47[a]	47[a]	0	0
B	25[b]	33[c]	8	35
C	34[c]	26[b]	8	24
D	22[c]	22[c]	0	0
E	27[c]	35[c]	8	24
F	39[b]	36[b]	3	8
G	29[c]	32[c]	3	11
H	35[c]	27[c]	8	24
I	21[c]	20[c]	1	5
J	29[c]	27[c]	2	7
Mean ±SD	30.8 ± 8.1	30.5 ± 7.9	|t0.17 = |	$p = 0.868$

Note: the numbers that represent differences in Table 1 are absolute values. Thus, it is not important which values are greater as both tests were identical and were conducted in a randomized order. The comparison is simply between these two absolute values. The t-value expressed in Table 1 represents the difference in the absolute value.
Exercise termination criteria.
[a] Maximal exercise duration completed.
[b] Volitional fatigue, and
[c] HR ≥ 90% HR_{max} (sustained >1 min).

While some subjects showed a significant initial decrease in T_{sk} during the first few minutes of exercise (initial cutaneous vasoconstrictor response), group mean T_{sk} increased rapidly throughout 20 min of exercise demonstrating a more curvilinear trend compared to the T_{rec} response over the same time course. While group mean T_{sk} reached a plateau at the 20 min point, subjects T_{sk} still demonstrated significant individual variability (Fig. 1). However, no significant difference in T_{sk} was found at any stage between the two trials. As expected, T_{sk} significantly increased during exercise between stages from baseline to end-exercise stage ($p < 0.001$). Nevertheless, the within-subjects analysis of the effect of the trial on T_{sk} appeared to be significant ($F = 5.18$, $p < 0.05$). This suggests a greater variability in T_{sk} within subjects.

HR increased rapidly during the first 5 min ($p < 0.001$) followed by a gradual increase for the remainder of exercise. Upon cessation of exercise (recovery stage), HR promptly decreased toward baseline values (Fig. 1). Similar group mean results were observed with a consistent range of SD between trials. This indicates that the exercise intensities at which the subjects performed were quite repeatable between separate trials. Additionally, SR did not significantly differ between trials. However, a greater variability between the subjects was noted in which the range of SD accounted for approximately one third of group mean in both trials (1.31 ± 0.52 kg h^{-1} for trial 1 vs. 1.17 ± 0.38 kg h^{-1} for trial 2; $p = 0.438$).

4. Discussion

In the present study, during two separate occasions, we measured the physiological responses to exercise while wearing PC under controlled environmental conditions (22 °C, 50% RH). The results have demonstrated that T_{rec}, HR, and maximal exercise tolerance time (a non-physiological measure but an important element in assessing PC performance) measures are highly repeatable both between separate trials and within subjects. However, measures of T_{sk} and SR are less repeatable in the present study based on a significant trial effect on T_{sk} and high variability in SR within subjects (perhaps due to differential

Table 2
Group mean data ($n = 10$) for rectal (T_{rec}) and mean skin temperature (T_{sk}), heart rate (HR), sweat rate (SR) in the two trials.

Variables (Mean ±SD)	Time	Trial 1	Trial 2	Between trials[a]		Within subjects[b]		
				|t|	*p*-value	Effect	*F*	*p*-value
T_{rec} (°C)	Baseline	37.03 ± 0.34	37.15 ± 0.34	1.08	0.310	Trial	1.38	0.270
	5 min	37.02 ± 0.31	37.14 ± 0.34	1.17	0.271	Time	139.34	<0.001
	10 min	37.09 ± 0.32	37.22 ± 0.35	1.26	0.241	Trial × Time	0.03	0.998
	15 min	37.23 ± 0.035	37.36 ± 0.36	1.28	0.234			
	20 min	37.38 ± 0.38	37.50 ± 0.40	1.15	0.281			
	End-exercise	37.76 ± 0.33	37.82 ± 0.31	–	–			
	End-rest	37.94 ± 0.36	37.99 ± 0.34	1.03	0.336			
T_{sk} (°C)	Baseline	32.64 ± 0.71	32.48 ± 0.86	1.13	0.286	Trial	5.18	0.049
	5 min	33.33 ± 0.82	33.11 ± 0.75	2.05	0.070	Time	223.79	<0.001
	10 min	34.19 ± 0.94	33.83 ± 0.80	1.64	0.136	Trial × Time	0.28	0.889
	15 min	35.30 ± 0.66	34.93 ± 0.39	2.20	0.055			
	20 min	35.75 ± 0.57	35.53 ± 0.31	1.45	0.182			
	End-exercise	36.03 ± 0.62	35.93 ± 0.36	–	–			
	End-rest	35.75 ± 0.66	35.60 ± 0.83	0.17	0.869			
HR (beats min^{-1})	Baseline	92.9 ± 17.6	92.1 ± 15.3	0.30	0.770	Trial	0.84	0.385
	5 min	143.2 ± 22.2	137.3 ± 21.8	1.20	0.260	Time	342.20	<0.001
	10 min	155.0 ± 22.6	154.1 ± 23.3	0.31	0.765	Trial × Time	0.40	0.805
	15 min	164.7 ± 21.4	162.3 ± 22.5	0.82	0.432			
	20 min	170.6 ± 21.2	169.2 ± 22.1	0.46	0.658			
	End-exercise	179.8 ± 16.5	180.8 ± 17.1	–	–			
	End-rest	133.8 ± 16.1	133.9 ± 18.5	0.33	0.752			
SR (kg h^{-1})		1.31 ± 0.52	1.17 ± 0.38	0.81	0.438			

[a] Between trials comparison for End-exercise to End-rest was performed with changes between the two time points.
[b] Within subjects analysis includes data from Baseline to 20 min time points. Note: the numbers that represent differences in Table 2 are absolute values. Thus, it is not important which values are greater as both tests were identical and were in randomized order. The comparison is simply between these two absolute values. The t-value expressed in Table 2 represents the difference in the absolute value.

recruitment of sweat glands, degree of acclimatization, etc.) (Taylor et al., 2008).

Physiological responses to exercise while wearing PC, compared to when not wearing PC, have been described by several investigators (Nunneley, 1989; Kraning and Gonzalez, 1991; McLellan et al., 1993; Montain et al., 1994); Dreger et al., 2006; Dorman and Havenith, 2009). It is generally agreed that, among other things, the added weight and insulation of PC contributes to the increase in metabolic heat production and to the reduction in evaporative heat loss capacity (Bugajksa et al., 2007). These are among the major factors that are responsible for the physiological and thermoregulatory strain. During exercise, increased T_{core} indicates an increase in body heat storage resulting from increased metabolic heat production (largely from skeletal muscle contraction) coupled with a reduced heat loss to the environment due to the encapsulating nature of PC (Sawka and Wenger, 1988; Bugajksa et al., 2007).

In the present study, T_{rec} response appeared to be quite repeatable as evidenced by 1) a consistent rate of increase of T_{rec} throughout exercise that did not differ between the two groups, 2) a similar T_{rec} observed at each time point examined between trials, and 3) no trial effect observed within subjects. This result is in line with a previous study by Jette et al. (1995) which demonstrated a strong repeatability of T_{rec} during exercise within both athletic clothing and PC in a similar environmental condition (20 °C, 50% RH). It is noteworthy that there was a significant delay (~5 min) for T_{rec} to reach a steady rate of increase after the onset of exercise (Fig. 1) and a continued steady increase in T_{rec} during 5 min of post-exercise rest. The delayed response of T_{rec} to thermal stress is also consistent with previously reported observations and has been attributed partly to an effect of greater insulation and greater heat capacity of the tissues surrounding the rectum (Sawka and Wenger, 1988; Nielsen and Nielsen, 1962; Saltin and Hermansen, 1966; Cranston et al., 1954).

Historically, T_{rec} has been identified as an "insensitive" indicator of body core temperature in that it does not promptly respond to changes in blood temperature (Nielsen and Nielsen, 1962; Saltin and Hermansen, 1966). Moreover, T_{rec} requires a relatively longer time to achieve a steady state compared to other measurement sites such as the esophagus (Nielsen and Nielsen, 1962). In fact, it has been suggested that esophageal temperature is a more sensitive indicator than T_{rec} in determining thermal strain among different levels of insulation used in PC (Kenny et al., 1999). However, in our study, utilization of an esophageal temperature probe was not a practical means of measuring T_{core} in our subjects wearing a respiratory protective device because a facepiece covering the mouth would preclude the use of an esophageal temperature probe. In contrast, T_{rec} can be measured more readily, provides a good index for an average internal body temperature (Saltin and Hermansen, 1966), is probably less influenced by external environmental conditions (Sawka and Wenger, 1988), has less individual variation during exercise, and is highly repeatable (Saltin and Hermansen, 1966; Saltin and Gagge, 1970). Thus, the preferred selection of measurement sites may vary with the experimental conditions of a study, but the present study suggests that T_{rec} is an adequate, and highly repeatable, measure of T_{core}.

HR responses also appeared to be highly repeatable both between trials and within subjects. The observation that a rapid increase in HR during exercise, (up to 70% HR_{max}) and thereafter a gradual increase to near HR_{max} (90%), is similar to other reports that examined the physiological effects of wearing a PC and SCBA (Manning and Griggs, 1983; Bruce-Low et al., 2007). These and other studies have also shown a significant contribution of combined PC and SCBA weight on an increased HR and metabolic cost to the wearer (Bruce-Low et al., 2007; White and Hodous, 1991). This finding also appeared to be in agreement with the present study in which the subjects' HR responses were greater while wearing PC than those unencumbered with PC (during baseline GXT tests) during exercise at 50% $\dot{V}O_{2max}$. It is possible that the increase in HR during this time was also due to the well-recognized phenomenon known as "cardiovascular drift".

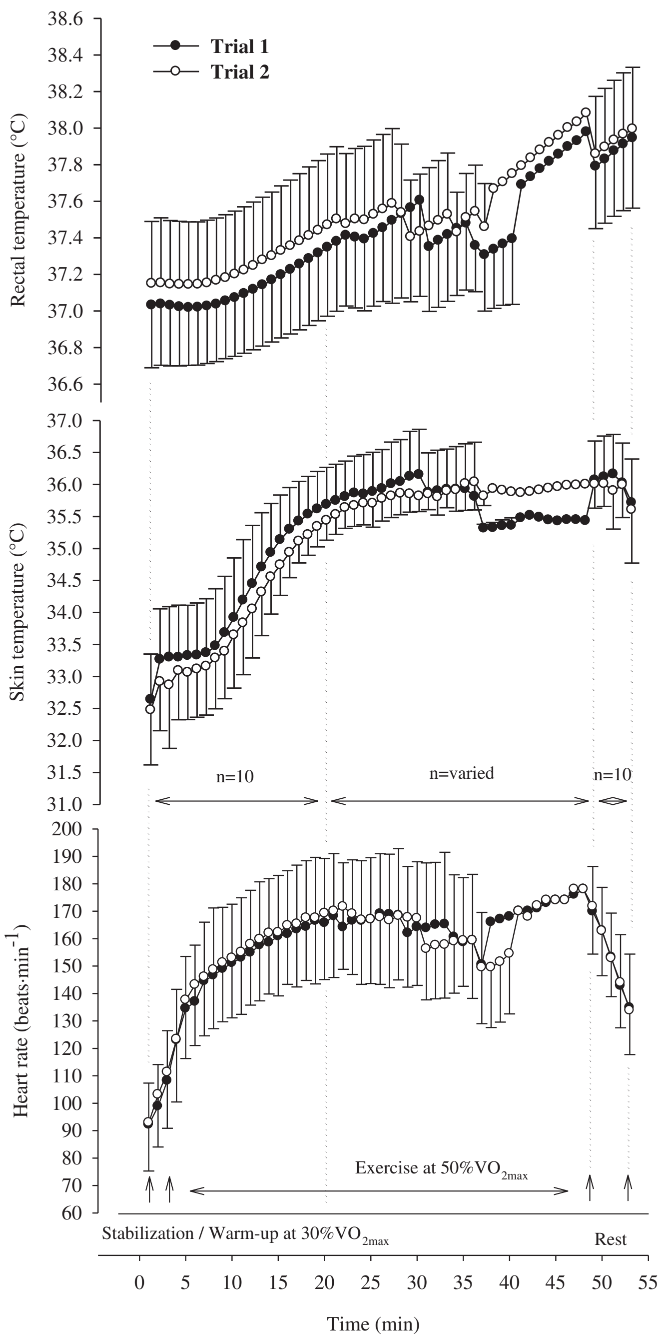

Fig. 1. Rectal temperature (T_{rec}), skin temperature (T_{sk}), and heart rate (HR) responses during the repeated experimental trials. Values are presented as group mean ± SD ($n = 10$).

Cardiovascular drift (decreased arterial, pulmonary, and central venous pressures resulting in a decreased stroke volume) occurs in response to redistribution of blood to the cutaneous circulation while supplying blood to the working muscle that results in an increased HR in order to maintain cardiac output (Rowell, 1993). Nevertheless, this phenomenon would have been present in all subjects exercising under identical conditions (Williams et al., 2011), so cardiovascular drift is probably not an important element in these comparisons.

During the present study, the subjects exercised at a relative workload of 50% $\dot{V}O_{2max}$, which had been previously calculated from the results of their maximal GXT. The relative workload was adjusted to account for the total weight of the PC and SCBA on each subject in order to reduce inter-subject variability and thus to reproduce increased T_{rec} relative to the metabolic rate (Saltin and Hermansen, 1966; Saltin and Gagge, 1970; Åstrand, 1960). It must be noted, however, that unlike the metabolic responses measured in the controlled setting of the laboratory in which all the subjects exercised at the same relative workload, the metabolic requirements for working in a real-life scenario while wearing a PC and SCBA are not relative since the weight of the PC and SCBA are approximately the same for all individuals. The PC and SCBA represented an absolute weight carried by subjects of varying size. For the smaller subject, the PC represented a greater percentage of his/her body weight so that the absolute workload (additional weight of PC and SCBA) relative to subject size would account for a reduction in exercise capacity between the subjects. Thus, a person with a lower body weight and lower aerobic capacity would work at a higher $\dot{V}O_2$ (Åstrand, 1960), compared to a larger and more fit person, while wearing the same PC and SCBA. Moreover, the differences in exercise duration seemed to be related more to the size of the individual rather than to his/her gender. Thus, the present data regarding the repeatability of HR should be interpreted with caution.

Previous investigations that examined tolerance time of individuals working in PC have reported that the level of clothing encapsulation (e.g., partial or full) plays as significant a role as other variables (e.g., aerobic fitness, hydration, acclimation, and work intensity) have on the ability to tolerate the physiological "burden" of the PC (Soteriades et al., 2011; Montain et al., 1994; Cheung and McLellan, 1998a, 1998b; Aoyagi et al., 1995). In the present study, mean tolerance time (exercise duration) appeared to be quite repeatable when presented as a group mean of 30.8 ± 8.1 and 30.5 ± 7.9 min for trial 1 and 2, respectively, under controlled conditions (e.g., fitness, hydration, etc.). However, concerns arise from differences in test performance time of up to 8 min (24–35%) between subjects. A possible explanation for these differences is that almost all of the subjects reached the test termination criteria of ≥90% HR_{max}, which was rapidly achieved within 20 min of the start of the exercise in individuals wearing both the PC and SCBA (Manning and Griggs, 1983).

One limitation of this study is that we did not include subjective or psychological measurements that may help determine the factors influencing and/or interacting with the subject's tolerance to wearing PC. The issue of the psychological effects (e.g., anxiety, claustrophobia, personal motivation) on performance limitations, while wearing PC, requires further study. Therefore, we do not have the data to determine the influence of the non-physiological component of the performance time. A second limitation is the low number of subjects ($n = 10$) which possibly resulted in a larger variability in the physiological measures or performance times. Nevertheless, given these limitations, the data still suggests that the subjects' physiological responses to wearing the PC were consistent with repeated testing.

The ability to predict the probable amount of sweat loss helps to determine the level of dehydration and plan for the adequate hydration to reduce thermal strain and increase performance of the subject. However, significant variations in SR have been documented even among heat acclimatized individuals with comparable levels of aerobic fitness (Sawka et al., 2007). This phenomenon is possibly due to differential sweat gland recruitment as one of many physiological responses to relieve heat strain (Taylor et al., 2008). Although the present study showed no statistical difference in SR between the trials, the high between-subject variation in SR make it difficult to derive specific conclusions regarding the SR response in the present study. Moreover, although there were no statistical differences between group means between trials analysis, the significant trial effect on T_{sk} within subject analysis seems to require further study to determine its potential repeatability in subjects wearing PC.

Another limitation was that the subject's $\dot{V}O_2$ was not verified after calculation for the additional weight of the PC and SCBA. This was not done due to the difficulty of making those measurements while the subject was wearing the SCBA. However, since relative metabolic work is expressed as $\dot{V}O_2$ in $mL \cdot min^{-1} \cdot kg^{-1}$, it was felt that dividing the $\dot{V}O_{2max}$ by the overall weight including the PC and SCBA, to determine the speed and incline of the treadmill would provide a reliable means of determining the relative workload. In any case, since all subjects were treated in the same way, comparisons between the two trials could be made in order to determine the ability to obtain similar physiological measures from test to test.

A final limitation was the possible ordering of the subjects. Every effort was made to avoid this ordering effect, however, some ordering was unavoidable (the order of each test was the same in the repeat trials). Although this ordering effect may have had a limited effect on the data, all subjects were treated in the same way thus mitigating this effect.

5. Conclusion

The present study has demonstrated that T_{rec} and HR are physiological variables that are more highly repeatable than SR and T_{sk} when compared between two separate PC user performance tests under controlled laboratory conditions. Additionally, while individual performance times were highly variable, aggregate or group performance times were also quite repeatable between tests. Thus, these variables may have the potential to be used as physiological indices to assess PC performance criteria and/or evaluation in hazardous occupational settings. Moreover, the results of this study indicate that similar physiological responses may be obtained from subjects who participate in repeated testing while wearing the same ensemble. The consistency of the physiological data obtained from repeated measurements suggests that the data may be used successfully evaluate the physiological burden of PC in future ensemble testing and certification protocols.

Disclaimer

The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of NPPTL or NIOSH/CDC. Mention of commercial products or trade names does not constitute endorsement by NPPTL or NIOSH/CDC. The authors do not identify any conflict of interests in the present research.

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