The Thermal Demands of Flood Rescue and Impacts on Task Performance

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Abstract

Objective: To determine the thermal demand of simulated Flood Rescue tasks and impacts on performance. Methods: Ten participants undertook two simulations: 'Cold' (4°C)-participants stood in knee height moving water (4.8km·h^{-1}), with simulated wind and rain for 60 min. 'Warm' (20°C)-participants performed 6x7 min walking in knee height moving water (3.2km·h^{-1}), pulling 10kg. Grip strength, manual dexterity, and jump height were measured pre and post. Results: The cold resulted in cooling of the great toe and finger (9.98 [0.84]°C and 10.38 [8.21-12.1]°C respectively). Jump height, manual dexterity and grip strength fell by 20%, 22% and ~13% respectively. In the 'Warm': heart rates were 157 (19)b.min^{-1}, oxygen consumption 30.62 (7.83)mL.kg^{-1}.min^{-1}, and sweat loss 1.06 (0.31)L. There were no differences in the physical tests. Conclusion: Flood Rescue represents significant, but different, challenges. Remaining static in the cold resulted in peripheral neuromuscular cooling, whilst exercising in the warm resulted in significant thermal challenge.

Keywords: Fitness, Flowing water, Personal Protective Equipment, Technician

Practitioner Summary

Little is known about the physical requirements, thermal profiles and optimum personal protective equipment for flood rescue. Flood rescue represents significant challenges. In the cold, emergency responders may be incapacitated by peripheral cooling. In the heat, they may be incapacitated by heat-related exhaustion. Consideration should be given to these risks.

1.0 Introduction

In comparison with the evidence based research that underpins other scenarios involving rescue personnel and their personal protective equipment (PPE), relatively little is known about the physical requirements, thermal profiles and optimum PPE for flood rescue (FR). FR can occur in a range of thermal conditions and PPE is required to be worn, challenging the thermal status of the rescuer. Cooling and heating in PPE during partial immersion (*i.e.*to the knee) in flowing water as occurs in FR is under researched. Convective cooling in water is maximised in water flow rates between 0.5 m.s^{-1} and 1.3 m.s^{-1} (2.88 km·h^{-1} and 4.68 km·h^{-1}; (Tipton & Golden, 1998)). Cooling of the superficial nerves and muscles, in particular of the limbs, quickly reduces functions like grip strength and manual dexterity (Tipton & Vincent, 1988). Nerve block can occur after 15 minutes in water at 15 °C reducing power output of a muscle by 3 % per °C fall in its temperature (Basbaum, 1973; Clarke, Hellon, & Lind, 1958; Douglas & Malcolm, 1955).

Due to FR responder's proximity to contaminated water, teams are required to wear PPE even in warm simulations. Thus increasing the potential for hyperthermia, the signs and symptoms of which range from light-headedness to unconsciousness and heat stroke (Tipton, 2015). If all of the heat produced by the body is prevented from passing to the environment due to clothing, a fatal level of heat storage can be reached in about 20 minutes when working moderately (Noakes, 1991).

Given the above, there is a need to consider the potential thermal demands of FR and the potential consequences for the performance of the physical tasks associated with FR. To undertake such an investigation, it is important to establish the critical tasks associated with FR

and characterise them in terms of their technique, criticality, frequency, intensity and duration. Internationally recognised methodologies for undertaking a task analysis have been recommended (Tipton, Milligan, & Reilly, 2013). This is achieved by task analysis which involves: reviewing standard operating procedures; direct observation; interviews and discussion groups with subject matter experts (SME) (Blacker et al., 2015; Milligan, Reilly, Zumbo, & Tipton, 2016; Reilly, Gebhardt, Billing, Greeves, & Sharp, 2015; Stevenson, Siddall, Turner, & Bilzon, 2016; Tipton et al., 2013).

This study investigated the thermal demands of FR and the consequences for physical task performance. The simulations chosen were based on typical 'Cold' and 'Warm' conditions as defined by SME. It was hypothesised that remaining static in the 'Cold' simulation would result in cooling resulting in significant decrements in physical performance, whilst exercising in the 'Warm' simulation would result in significant increases in deep body temperature and physical effort during the simulation.

2.0 Methods

2.1 Participants

Written informed consent was obtained from the participants before starting the study and favourable ethical opinion was granted by the Science Faculty Research and Ethics committee (SFEC 2017-110). On the basis of a power calculation, ten male participants volunteered and took part in the study (mean (SD) Age, 37 (11) years; Height, 179.44 (6.11) cm; Mass, 85.80 (7.12) kg). Sum of Skinfolds, 101.14 (48.36) mm. They were recruited from FR teams

throughout the UK (n = 7, minimum experience 2 years) and members of the University (n = 3) who had been familiarised with wading through moving water.

2.2 Procedures

On arrival to the laboratory (Air Temperature - 19.07 [1.63] °C; Barometric Pressure – 1012 [11] mbar; Humidity - 64 [6] %) participants' height to the nearest 0.1 cm (Seca Ltd, Leicester, UK), nude mass to the nearest 0.05 kg (Model B150S Sartorious, UK), and skinfold thickness at eight sites (biceps, triceps, subscapular, iliac crest, supraspinale, abdominal, front thigh, medial calf, Note: all eight sites were summed), were measured. Pre- and post-physical performance tests were performed in air in the laboratory involved: a counter movement jump (CMJ), maximum grip strength, and a timed manual dexterity task (unscrew and re-screw a nut and bolt). All pre- and post-tests were undertaken wearing flood rescue PPE (SafeQuip, UK) which included: a long sleeve thermal vest and trousers; dry suit; gloves, steel toe capped boots; thermal socks; helmet; helmet liner ('Cold' simulation only) and a personal flotation device. The total mass of the kit was 9.25 kg. Participants then undertook two simulations, in a controlled environmental laboratory, based on advice from SME. The SME consisted of three experienced (>5 years undertaking flood rescue) FR emergency responders, who were proficient in performing, training, and leading flood rescues, from Surf Life Saving GB, and the Royal National Lifeboat Institution. Two simulations were selected based on the activities likely to be undertaken during a rescue performed on a typical cold and hot day in the UK. Experimental air and water temperatures were based on available data from the UK Met Office 2016 to 2017. The flume flow rates were based on the Flood Rescue National Enhancement Project (Defra, 2012) which

stipulates a technician should be able to demonstrate wading up to class 2 swift water (i.e. water moving faster than walking pace is too rapid for a wading to take place).

These simulations were performed at least 24 hours apart in a thermostatically controlled climatic chamber containing a swimming flume:

   i.   The 'Cold' simulation required participants to stand immersed to the knee in the swimming flume with moving water flowing at a rate of 4.8 km·h^{-1}, with simulated rain (a shower head place directly above the participant) for 60 min (Figure 1). Air temperature, water temperature wind speed and humidity were set to 4 °C, 7.7 °C, 16 km·h^{-1} and 80% respectively. Due to the constant addition of water to the flume from the simulated rain, water was removed at regular intervals to keep it at knee height.

INSERT FIGURE 1 HERE

   ii.   The 'Warm' simulation consisted of six 7 min stages with 3 min rest. Participants were immersed to approximately knee height and walked from one end of the swimming flume to the other (3.30 m) at a speed of 2.16 km·h^{-1}, in water flowing at 3.2 km·h^{-1}. Participants walked into the flow of water pulling a 10 kg load attached to a 1:1 pulley system (Figure 2). On reaching the end of the flume participants turned around and walked with the flow of water, controlling the release of the 10 kg (100 N static force). The load represented pulling a rescue boat. Air temperature, water temperature humidity, wind speed and radiant heat load were 20 °C, 15.6 °, 40 %, 0 km·h^{-1}, and 500 W·m^{-2} respectively.

INSERT FIGURE 2 HERE

2.3 Measurements

The measurements taken were selected as they represented the physical parameters of the tasks FR emergency responders might be expected to perform following a rescue.

2.3.1 Pre and Post exposure tests (collected immediately before and after each simulation).

2.3.1.1 Calculation of Sweat Loss

Nude body mass was measured to 0.01 kg (Ohaus, US) on arrival to the laboratory and following the simulations and post-test measures. Water consumption was monitored and factored into sweat loss calculations (Pre mass − Post mass[+ water consumption]).

2.3.1.2 Counter Movement Jump (CMJ) – used to simulate the activation of the muscles required to get into a rescue boat. The participant, wearing full PPE, stood as still as possible on the mat (Takei, Japan) with weight evenly distributed over both feet. Hands were placed on the hips, and stayed there throughout the test. The participant squatted down to a self-selected depth then immediately jumped vertically as high as possible, landing back on the mat on both feet at the same time. This was repeated three times with 30 s rest between each jump. The best result (height jumped, cm) of the three attempts was recorded.

2.3.1.3 Grip Strength – used to simulate the activation of the muscles used in tasks such as casualty handling and evacuation. Grip strength was measured using a Precision Dynamometer G100 (Biometrics Ltd, Gwent, UK) accurate to 0.1 kg. Maximum grip strength tests were undertaken three times for each hand, allowing 30 s rest between tests of the same hand (Douris, Mckenna, Madigan, Cesarski, & Lu, 2003). The dynamometer was zeroed before each test; the elbow was at 90 degrees. The hand did not tilt, rest on the leg or table, and grip was a maximal squeeze.

2.3.1.4 Manual Dexterity – fine motor tasks such as tying knots. To represent a fine motor skill task, participants were asked to unscrew and re-screw a large nut and bolt using their hands (Figure 3). The total time taken to fully unscrew and re-screw the nut was recorded.

2.3.2 Variables monitored during the exposures

2.3.2.1 Deep body temperature. Tre was measured with a thermistor (Sharktooth®, MIE, UK) inserted 10 cm beyond the anal sphincter. The Tre data were obtained via telemetry (Sharktooth®, MIE, UK), displayed in real time and recorded.

2.3.2.2 Skin temperature and heart rate. Skin temperature (Tsk) of the biceps, chest, thigh, shin, middle finger, great toe (Sharktooth®, MIE, UK) and heart rate (HR, Sharktooth®, MIE, UK), were collected, displayed in real time and recorded continuously by telemetry (Sharktooth®, MIE, UK). Weighted mean skin temperature (Tsk) was calculated according using 0.3*(Biceps + Chest) + 0.2*(Thigh + Shin) (Ramanathan, 1964).

2.3.2.3 Oxygen consumption. Expired gas samples were obtained with the participants seated at rest for 5 minutes prior to entering the climatic chamber using a Douglas Bag. Once in the climatic chamber expired gas were sampled for one minute. Samples were taken during the 5th and 55th minute in the 'Cold' simulation and 15th and 55th minute in the 'Warm' simulation as not to interfere with the activity of the participant. The gas sample was analysed for oxygen and carbon dioxide factions (Rapidox 1100L, Cambridge Sensotec, UK) and the volume (Dry Gas Metre 230V, HaB Direct, UK) quantified in order to calculated oxygen consumption (STPD (Weir, 1949)).

2.3.2.4 Subjective responses. Rating of Perceived Exertion (RPE, Borg, Hassmén, & Lagerström, 1987), thermal comfort and sensation (Davey, Reilly, Newton, & Tipton, 2007) and skin wettedness (Filingeri, Fournet, Hodder, & Havenith, 2014) were used to quantify subjective perceptions of exertion and thermal comfort placed on the participant during both **simulation**s. At the end of each minute, the participants were asked to provide an RPE using the CR-10 RPE scale. Participants reported thermal comfort, sensation and skin wettedness on sliding scales from 'very uncomfortable' to 'very comfortable', 'very cold' to 'very hot' and 'very dry' to 'very wet' respectively.

2.4 Data Analysis

Data were statistically analysed using IBM SPSS 24.0 for Windows (SPSS Inc, Chicago, IL). Tests of normality were conducted to assess, if the data were parametric using Skewness and Kurtosis. Data are presented as mean (SD) or median (range) as appropriate. Paired samples t-tests were conducted to determine if any significant differences existed pre and post exposure.

Effect sizes were calculated using Cohen's *d* Statistic (Cohen, 1988). Non-parametric data were analysed using Wilcoxon Signed-rank test. Effect sizes were calculated using the Pearson's (r) statistic (Field, 2013).

3.0 Results

3.1 Cold Simulation

The temperature at the great toe fell significantly ($t_{(9)}$ =9.626; p < 0.001; d =3.94) from 26.92 (6.02) $^{\circ}$C to 9.98 (0.84) $^{\circ}$C (Figure 1). Similarly median (range) finger temperatures fell significantly ($Z_{(9)}$ =-2.803; p = 0.005; r =-0.72) from 34.45 (14.00) $^{\circ}$C to 10.38 (3.89) $^{\circ}$C (Figure 4). Tsk temperature fell significantly ($t_{(9)}$ =10.979; p < 0.001; d =0.48) from 34.76 (1.22) $^{\circ}$C to 27.29 (2.19) $^{\circ}$C.

INSERT FIGURE 4 HERE

Tre did not change significantly ($t_{(7)}$=0.710; p=0.500; d = 0.17) from the start of the immersion (37.55 (0.45) $^{\circ}$C) to 60 minutes (37.48 (0.36) $^{\circ}$C) (Figure 2). Heart rate was significantly higher (p<0.05) at time points 0, 5, 10 and 15 compared to time point 60. From time point 20 to 60 there were no significant differences (p>0.05) in HR (Figure 5).

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INSERT FIGURE 5 HERE

Oxygen consumption rose significantly ($t_{(9)}$ =-3.402; p = 0.008; d =-0.96) from the 5th minute (7.56 (1.88) mL.kg^{-1}.min^{-1}) to the 55th minute (10.04 (3.13) mL.kg^{-1}.min^{-1}) (Figure 6).

INSERT FIGURE 6 HERE

Figure 7 shows the subjective responses recorded in both simulations. Participants did not find the 'Cold' simulation physical demanding, but did report feeling very cold and uncomfortable by the end.

INSERT FIGURE 7 HERE

Jump height fell significantly ($t_{(9)}$ =7.693; p < 0.001; d =0.91) by 20 %. Manual dexterity significantly ($Z_{(9)}$ =-2.599; p = 0.009; r=-0.82) deteriorated by 22 % and grip strength fell significantly ($t_{(9)}$ =4.552; p = 0.001; d =1.14) by 14 % in the dominant hand and by 13 % in the non-dominant ($t_{(9)}$ =4.859; p = 0.001; d =0.87) (Table 1).

INSERT TABLE 1 HERE

3.2 Warm Simulation

Initially participants were asked to work continuously for 60 minutes, walking at 2.16 km.h^{-1} in water flowing at 4.8 km·h^{-1}; however, the first participant found this impossible and following 10 minutes of exercise was exhausted and had a predicted time of ~45 minutes to reach a deep body temperature of 40 °C. As a consequence, the requirements were modified as described in the methodology. By the end of the exposure to the revised simulations, average heart rates were 157 (19) b·min^{-1} (Figure 8), this still represented 87% of predicted average maximum heart rate. Oxygen consumption averaged 30.62 (7.83) mL·kg^{-1}.min^{-1} during the final 5 minutes (Figure 6).

INSERT FIGURE 8 HERE

Participants reported feeling very warm and uncomfortable with a high skin wittedness (Figure 4). The level of discomfort reported was similar in both simulations, but for different reasons. In the cold it was cold extremities and discomfort due to mild shivering. In the heat is was high deep body temperature and perceptions mot probably related to central fatigue. Average sweat loss was 1.06 (0.31) L following exposure. Tre significantly ($t_{(7}$=-7.434; p < 0.001; d =-2.95) increased for the start to the end of the simulation (Figure 9).

INSERT FIGUE 9 HERE

Jump height, grip strength, manual dexterity did not change significantly (p>0.05) pre and post exposure (Table 2).

INSERT TABLE 2 HERE

4.0 Discussion

This was the first investigation into the physical and thermal demands associated with two typical FR simulations. The simulations observed were those regarded by subject matter experts as 'Cold' and 'Warm'; it is likely that most FR simulations fall between these conditions. The experienced FR emergency responders who volunteered for the study reported that the simulations, including workload in the 'Warm' simulation were realistic. The results demonstrate significant physical impairment following both simulations but the nature of that impairment, as hypothesised, differed.

In the 'Cold' simulation, the primary problem was associated with peripheral neuromuscular impairment resulting in physical incapacitation on tests requiring muscle function. The reduction in muscle function (hand and leg) ranged between 13 – 22 % after one hour in 'Cold' simulation. This reduction is due to the direct effect of cooling on neuromuscular function (Castellani & Tipton, 2016). Maximal dynamic strength, power output, jumping and sprinting performance are reduced by 4 to 6 % per °C reduction in muscle temperature down to 30 °C (Bergh & Ekblom, 1979). At nerve temperatures below 20 °C, nerve conduction is slowed and action potential amplitude is decreased (Douglas & Malcolm, 1955). Nerve block may occur after exposure to a local temperature of between 5 and 15°C for 1–15 minutes (Basbaum, 1973; Clarke et al., 1958).

The implication for FR is that with time in cold conditions emergency responders may find it increasingly difficult to perform fine motor skills *e.g.* untying ropes and tasks where leg power is required *e.g.* jumping into/manoeuvring a rescue boat. These decrements in performance should be taken into consideration when determining the physical requirements needed by FR emergency responders. Typically, selection criteria are determined when individuals are thermoneutral, therefore a technician just passing a required physical standard when normothermic may fail to achieve that standard when cold. This has implications for operational capability during rescues, such considerations have been recognised in other occupations (Baumgartner, Gruse, Flerlage, & Hanley, 2017).

On a health-related issue, it is worth noting that the peripheral skin temperatures recorded during the cold condition (circa 10 °C) and the circumstances of that condition (dependent limb, compressed tissues due to footwear and immersion) are very close to those associated with the

acquisition of a non-freezing cold injury (NFCI), particularly when exposure times are extended (Francis & Golden, 1985). The pathogenesis and pathology of NFCI are poorly understood, but the life-long consequences of this injury are well-recognised as: cold sensitivity, persistent intractable pain and hyperhidrosis (Golden, Francis, Gallimore, & Pethybridge, 2013). NFCI is a major cause of disability compensation claims within the military ("Lessons from history: morbidity of cold injury in the Royal Marines during the Falklands Conflict of 19822017," 2018) In the 'Warm' simulation, despite being immersed to mid-thigh in flowing cool water, the combination of exercise-related heat production and warm ambient conditions resulted in an uncompensable increase in deep body temperature (Figure 6). This increase, plus the high heart rates, oxygen consumptions and ratings of perceived exertion all suggest that in this condition people were working near their maximum capability. Having introduced the work-rest schedules to the protocol, the subsequent oxygen consumptions and heart rate values reported in the 'Warm' FR simulation still represented 'extremely heavy work' (Åstrand, Rodahl, Dahl, & Strømme, 2003). The metabolic requirements experienced during this simulation (30.62 (7.83) mL.kg^{-1}.min^{-1}) are comparable to those reported for mud rescue technicians (32.85 (5.79) mL.kg^{-1}.min^{-1}) pulling a rescue sled weighing 61 kg across estuary mud at a median (range) speed of 2.61 (0.56) km·h^{-1} (Milligan, House, & Tipton, 2017).

It is important to consider what percentage of an individual's maximum capacity performing a task such as FR should represent. When determining this percentage, consideration should be given to the duration of the task and its importance. For example, it is permissible to allow employees to work at maximum capacity for short durations, followed by rest, or in an emergency (Goldman, 2000). However, it is not thought acceptable to expect individuals to

routinely work at their maximum capacity, to do so will result in fatigue, with a consequent decrement in performance and a potential increase in the likelihood of accidents (*e.g.* trips and falls (Parijat & Lockhart, 2008)). Louhevaara Louhevaara, Smolander, Korhonen, and Tuomi (1986) Goldman (2000) suggest that individuals working for approximately one hour could do so if the task represents no more than 60 % of their maximum oxygen uptake ($\dot{V}O_{2max}$). On the basis of the data collected in the present study, this would mean FR emergency responders would require a $\dot{V}O_{2max}$ of approximately 51 mL.kg^{-1}.min^{-1}. The percentage of sustainable $\dot{V}O_{2max}$ (calculated based on body mass not including PPE) for intermittent work has not been documented, therefore thought needs to be given to specific work-rest scheduling of FR activities in the heat, and a consequent aerobic fitness requirements.

In 'Warm' conditions, the physical demand of work is compounded by the additional cardiovascular demand of high body temperatures, this combination can lead to a switch to anaerobic metabolism and early heat exhaustion (Cheuvront, Kenefick, Montain, & Sawka, 2010; Ely, 2010). An unchecked increase in deep body temperature can result in heat exhaustion at a deep body temperature of about 40 °C (Nybo & Nielsen, 2001) and heat stroke, a critical medic condition, at a deep body temperatures of >40.5 °C (Tipton, 2015). The proximity of the 'Warm' simulations to the circumstances necessary to produce heat exhaustion was exemplified by the first participant, an experienced FR technician, who found it impossible to undertake continuous work for more than 10 minutes; his increase in deep body temperature during this period can be extrapolated to predict heat exhaustion in 43 minutes and heat stroke in 60 minutes (assuming he was able to continue work). The changes in the experimental design necessitated by this response provides a clue as to how the risk of heat illness can be managed with FR emergency responders. This includes the expedient use of work-rest schedules, plus hydration

strategies, cooling strategies during rest periods and wearable physiological monitoring equipment. These interventions should help avoid heat-related health problems and optimize FR technician performance (Notley, Flouris, & Kenny, 2018; Tipton, 2015).

5.0 Conclusions

It is concluded that FR in both 'Cold' and 'Warm' simulations, reported here, represent significant, but different challenges. In the cold, emergency responders may be incapacitated by peripheral cooling, in the heat, they may be incapacitated by heat-related exhaustion. The hypotheses are accepted. Consideration should be given to elucidating and expanding these initial findings as well as exploring different methods of mitigating the risks identified.

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Tables

Table 1. Mean (SD) physical assessment data (Counter movement jump, Manual dexterity, Grip strength of the dominant and non-dominant hand) pre and post the 'Cold' flood rescue simulation (n=10).

Physical Assessment	Pre exposure	Post exposure
Counter movement jump (cm)	39.10 (9.24)	31.20 (8.12)**
Manual dexterity (s)*	46 (22)	58 (31)^
Grip strength – dominant (kg)	49.40 (6.95)	42.24 (5.53)**
Grip strength – non-dominant (kg)	47.03 (6.67)	41.28 (6.56)**

*Data presented as median (range); ** significant difference p<0.001; ^ significant difference p<0.05

Table 2. Mean (SD) physical assessment data (Counter movement jump, Manual dexterity, Grip strength of the dominant and non-dominant hand) pre and post the 'Warm' flood rescue simulation (n=9).

Physical Assessment	Pre exposure	Post exposure
Counter movement jump (cm)	36.75 (7.85)	37.88 (8.27)
Manual dexterity (s)*	40 (24)	37 (20)
Grip strength – dominant (kg)	47.63 (5.30)	45.30 (6.73)
Grip strength – non-dominant (kg)	45.30 (6.73)	45.86 (6.79)

* Data presented as median (range)

List of Figures
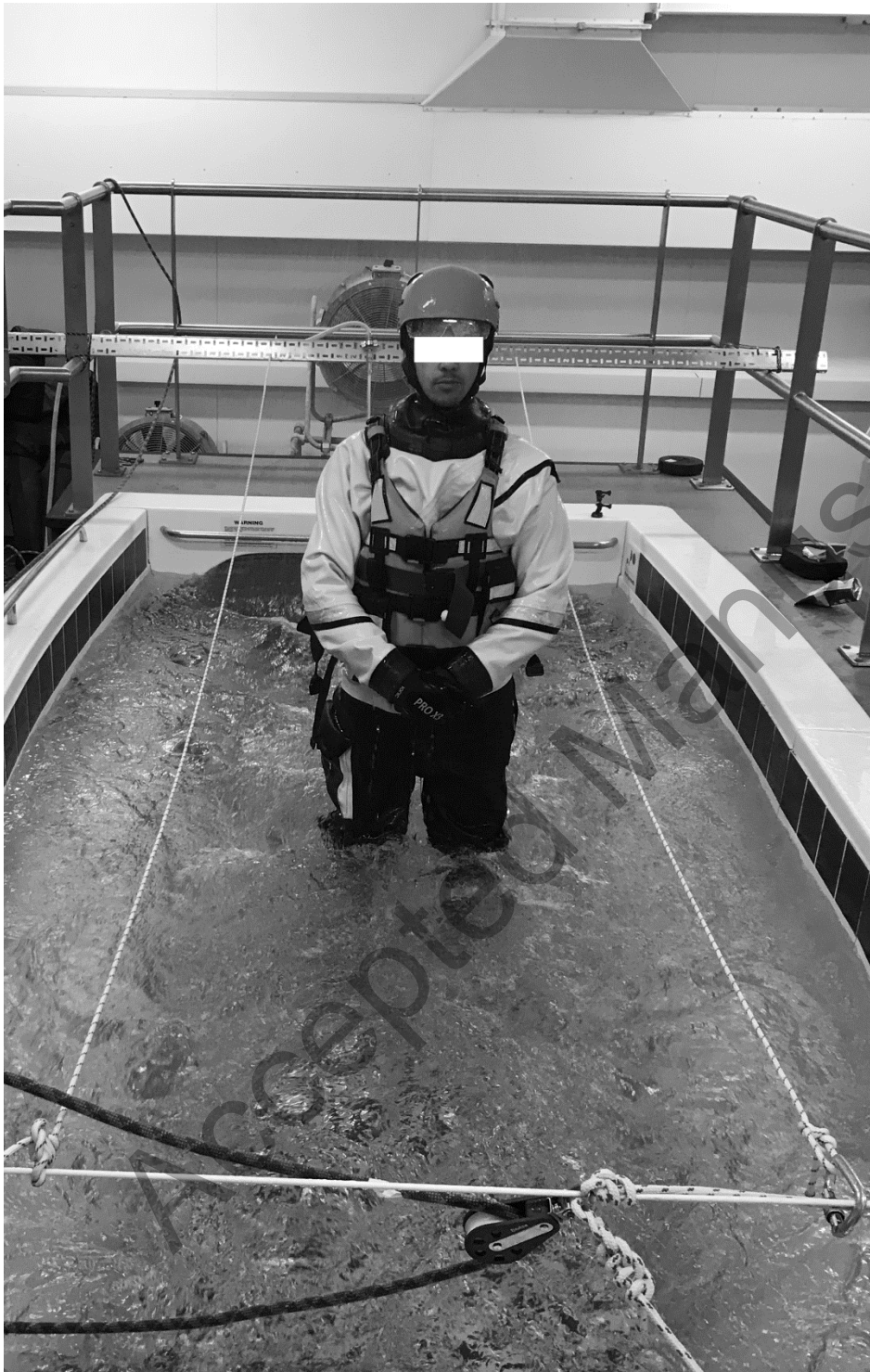
Figure 1. An example of a participant standing in the moving water during the 'Cold' simulation.

Figure 2. An example of a participant pulling the 10 kg load into the flow of the water during the 'Warm' simulation.
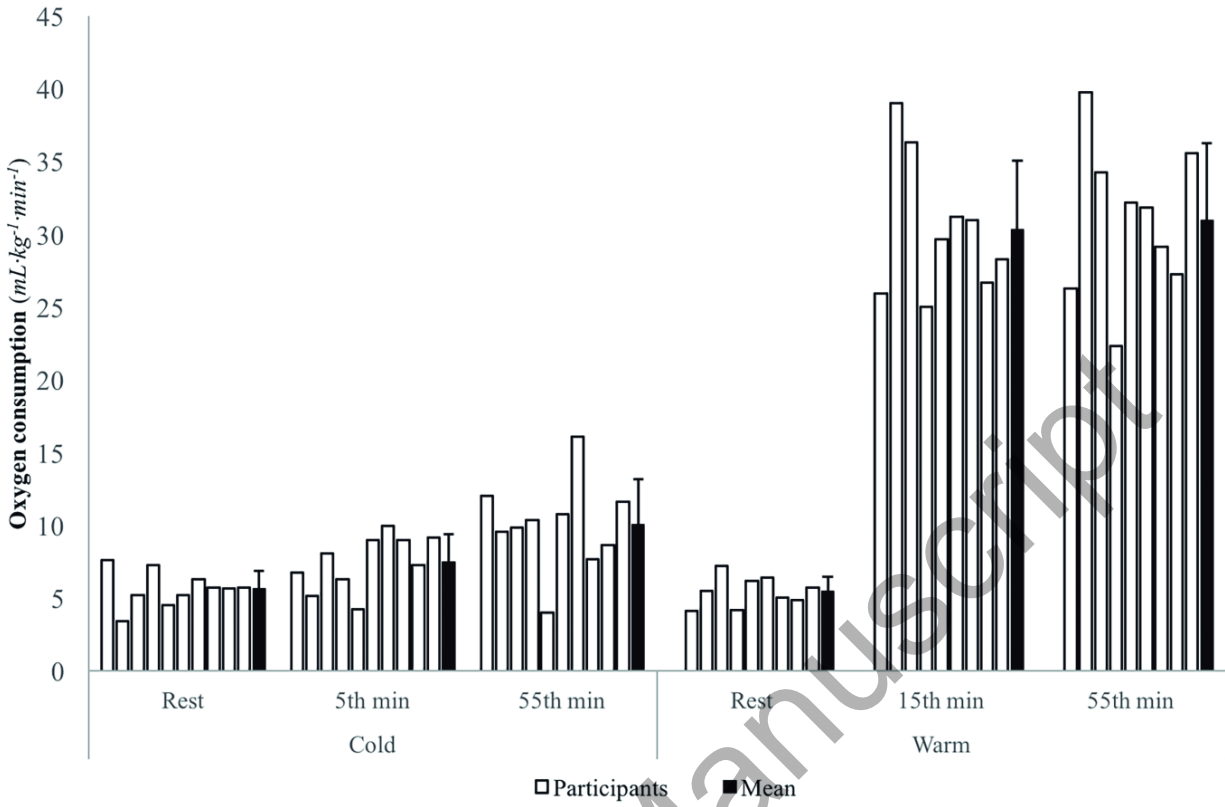
Figure 3. The nut and bolt task.
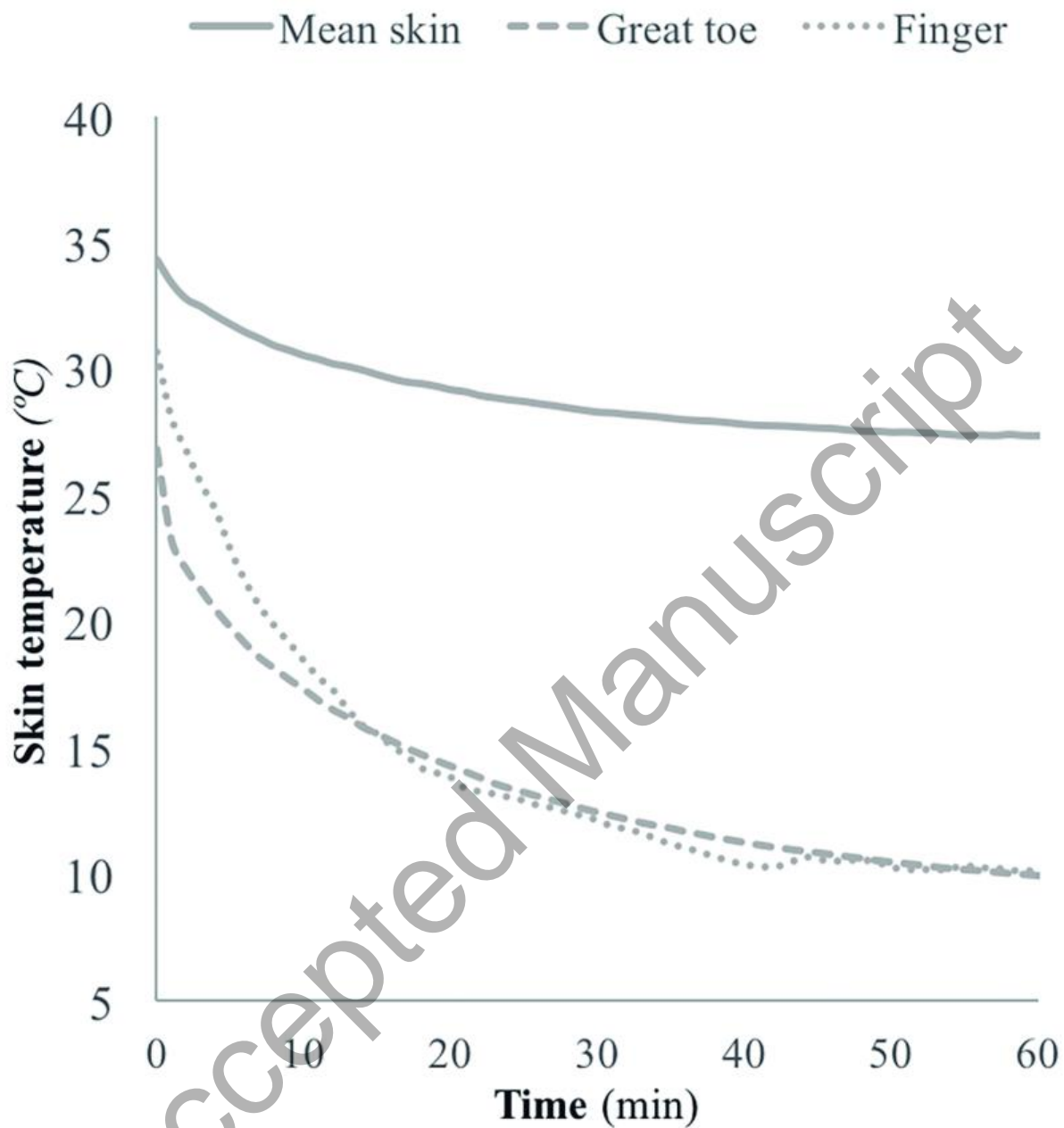
Figure 4. Mean skin, great toe and finger temperature (°C) during the 'Cold' simulation. Note:
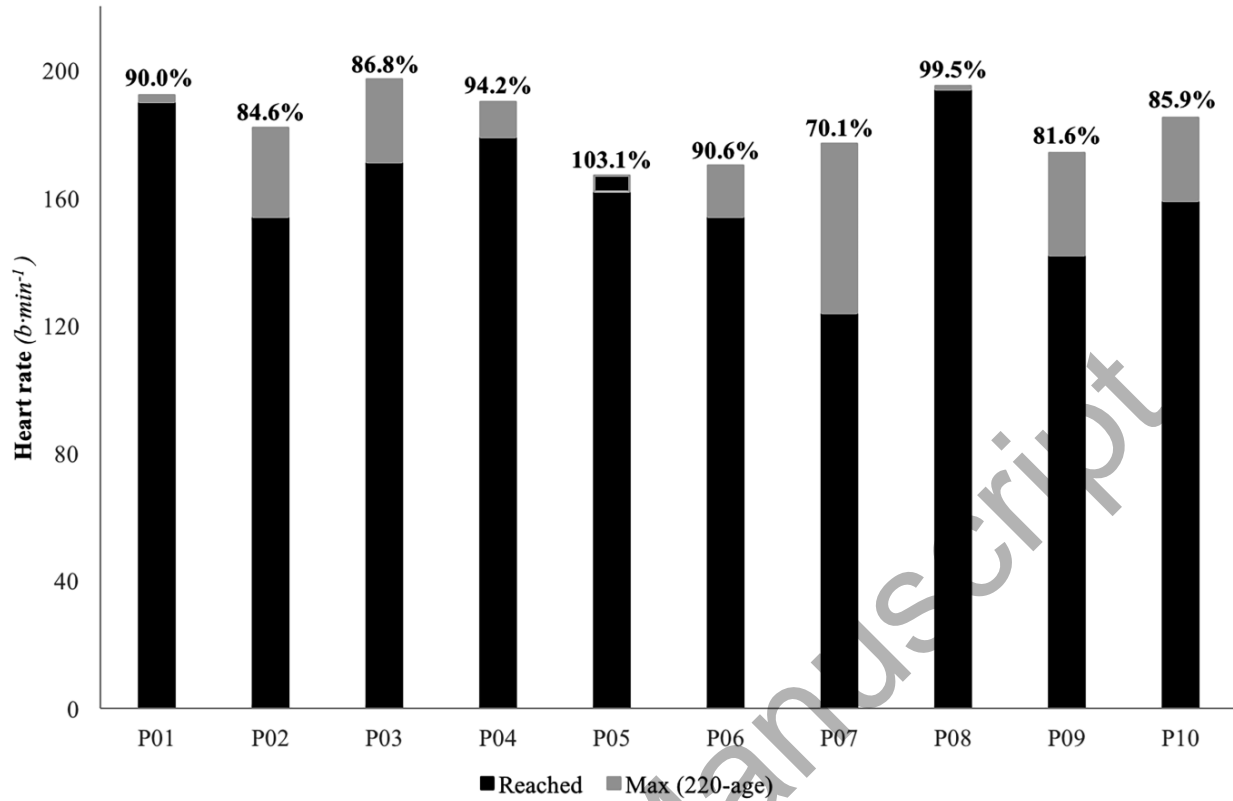Standard deviations are omitted for clarity (n=10).

Figure 5. Tre (°C) and heart rate (b.min^{-1}) during the 'Cold' simulation. Note: Standard deviations are omitted for clarity (n=10).

Figure 6. Oxygen consumption (mL.kg^{-1}.min^{-1}) for both **the 'Cold' and 'Warm' simulations.** Oxygen consumption is presented for each participant (white columns) and mean (SD [black columns]) (n=10).
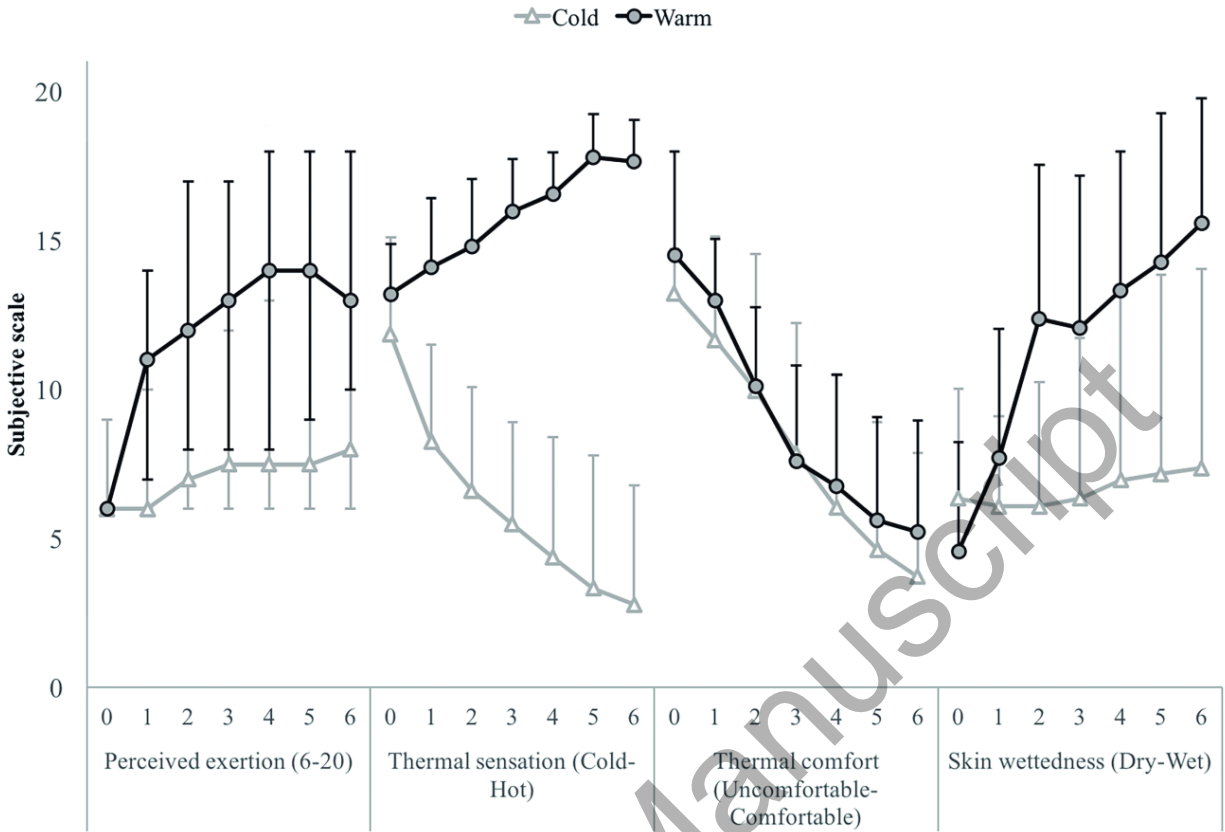
Figure 7. Rate of perceived exhaustion (median [range]), thermal sensation and skin wettedness (mean [SD]) for the start and on completion of exercise during the 'Cold' (n=10) and the 'Warm' simulation (n=9).

Figure 8. Peak heart rates observed (black columns) against predicted maximum HR (grey columns [HRmax = 220 – age]) during the 'Warm' simulation (n=10).
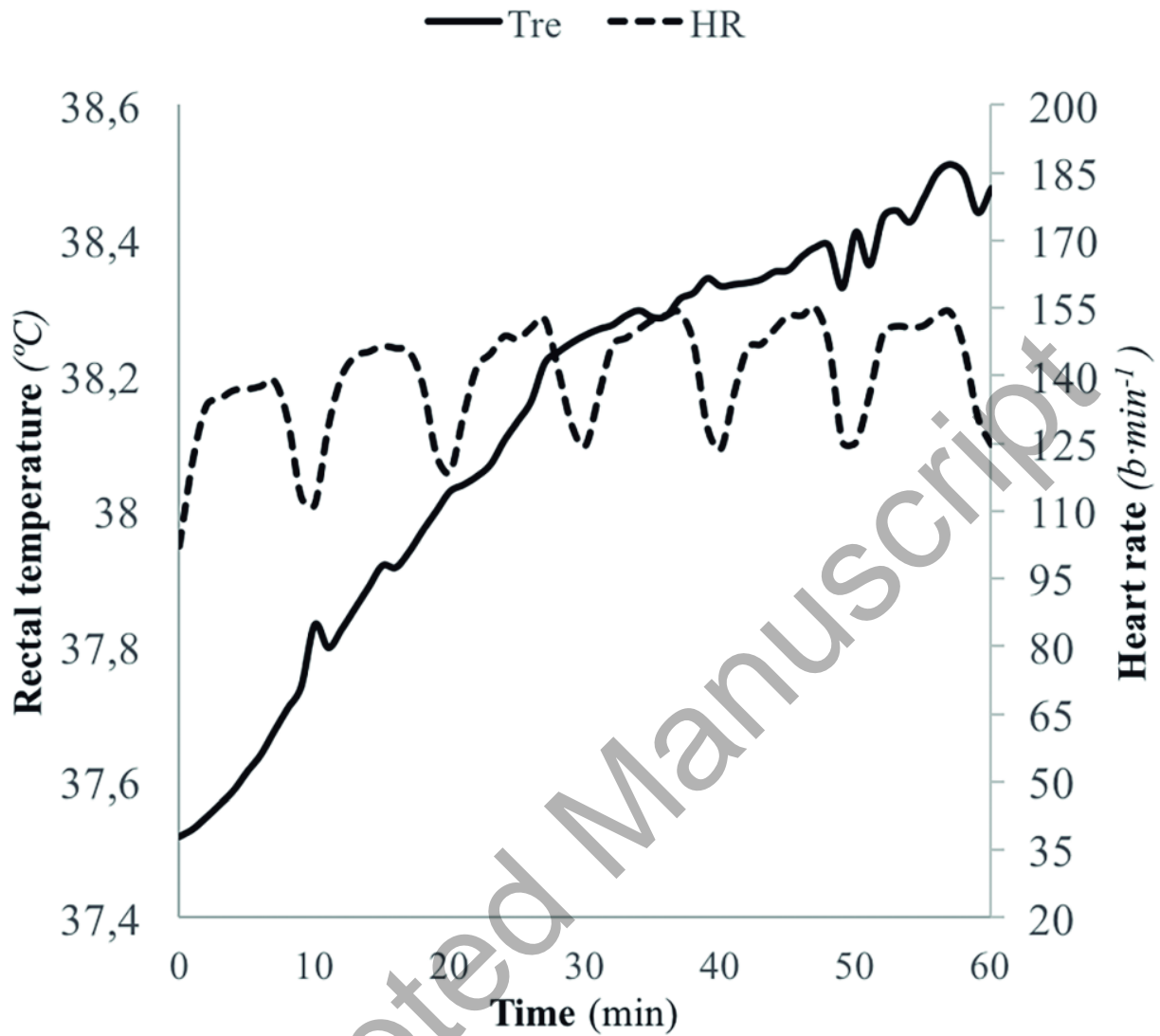
Figure 9. Tre and heart rate per minute during the 'Warm' simulation. Note. Standard deviations are omitted for clarity (n=10).