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Correction factors for assessing immersion suits under harsh conditions

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ABSTRACT

Many immersion suit standards require testing of thermal protective properties in calm, circulating water while these suits are typically used in harsher environments where they often underperform. Yet it can be expensive and logistically challenging to test immersion suits in realistic conditions. The goal of this work was to develop a set of correction factors that would allow suits to be tested in calm water yet ensure they will offer sufficient protection in harsher conditions. Two immersion studies, one dry and the other with 500 mL of water within the suit, were conducted in wind and waves to measure the change in suit insulation. In both studies, wind and waves resulted in a significantly lower immersed insulation value compared to calm water. The minimum required thermal insulation for maintaining heat balance can be calculated for a given mean skin temperature, metabolic heat production, and water temperature. Combining the physiological limits of sustainable cold water immersion and actual suit insulation, correction factors can be deduced for harsh conditions compared to calm. The minimum in-situ suit insulation to maintain thermal balance is $1.553-0.0624 \cdot T_W + 0.00018 \cdot T_W^2$ for a dry calm condition. Multiplicative correction factors to the above equation are 1.37, 1.25, and 1.72 for wind + waves, 500 mL suit wetness, and both combined, respectively. Calm water certification tests of suit insulation should meet or exceed the minimum in-situ requirements to maintain thermal balance, and correction factors should be applied for a more realistic determination of minimum insulation for harsh conditions.

1. Introduction

Many industries require their personnel to work or travel over open water, which in the vast majority of cases is well below the thermoneutral water temperature of 35.5 °C for naked humans to maintain a deep body temperature of ~37 °C (Park et al., 1983). As a result, supplemental thermal protection is required to increase safety and survival. An immersion suit is a lifesaving appliance (LSA) designed to provide flotation, reduce the severity of the Cold Shock Response (CSR), and delay the onset of hypothermia (CGSB, 2005). As prescribed by the International Maritime Organization (IMO), a certified insulated immersion suit should minimize the CSR and prevent a drop in deep body temperature from exceeding 2 °C after six hours of immersion in 0–2 °C calm, circulating water (IMO, 2010). Various standards across the world (e.g. Canadian General Standards Board (CGSB, 2005); International Organization for Standardization (ISO, 2002)) specify a similar test protocol for certifying the thermal protective properties of insulated and non-insulated immersion suits.

Recent marine accidents such as the sinking of the *Check Mate III* (Frampton and Savage, 2008) and the crash of Cougar Flight 491 (TSB, 2010) have called into question the accuracy of predicting the performance of immersion suits under harsh conditions based on calm water certification tests. Previous investigations by others on the thermoregulatory responses of people in immersion suits compared the effects of wind and waves to calm water that have resulted in equivocal findings. Previous studies by Hayes et al. (1985), Steinman et al. (1987), and Ducharme and Brooks (1998) found that immersion in a wind and wave condition increased

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heat loss without any significant decrease in deep body temperature. A subsequent study by Tipton (1991) found that immersion in turbulent conditions caused an uncompensable level of heat loss that exceeded the capability of the thermoregulatory system which resulted in a significant decrease in deep body temperature.

These discrepancies were the justification for our recent experimental investigation of the effects of wind and waves on predicted survival times (Power et al., 2015). We confirmed that immersions in wind and waves will significantly increase heat loss compared to calm water, and that predicted survival time is reduced as a consequence, which is exacerbated as water temperature decreases. However, with adequate insulation protection to ensure that the heat loss is compensable thus keeping deep body temperature stable, the predicted survival times can exceed 36 h, at which point factors other than hypothermia will most likely be the cause of death with continued immersion (Keefe and Tikuisis, 2008).

The results from our previous work emphasize the importance of testing immersion suits in conditions more representative of those found during mid to high latitude marine accidents (i.e. wind, waves, and near freezing temperatures) since testing in "calm, circulating water" will likely overestimate insulation performance. Among the challenges associated with testing immersion suits in wind and waves, there are few facilities in the world capable of creating wind and wave conditions representative of offshore environments in a repeatable manner. Additionally, it is expensive and logistically challenging to test in these unique facilities, and the cost of doing so may be beyond the resources of immersion suit manufactures.

A much more feasible and cost effective method for testing immersion suits is to convert the measured suit insulation under temperature-controlled calm conditions to harsher conditions by factoring in the increased heat loss due to wind and waves. The development of such correction factors is the aim of this paper.

2. Methods

2.1. Participants

Two human experimental studies were conducted to acquire the data necessary to analyze heat loss and to calculate the insulation requirements. The National Research Council of Canada (NRC) Research Ethics Board approved both studies (REB#:2008-68; 2009-67) in which a total of 22 healthy participants took part. Twelve males participated in Study 1 (Mean [SD] Age: 23.9 [3.3] yrs; mass: 83.2 [4.9] kg; height: 1.8 [0.05] m; surface area (SA): 2.0 [0.1] m^2; body fat percentage (BF%): 16.8 [4.1]%) and 10 participated in Study 2 (Age: 25.0 [5.6] yrs; mass: 79.2 [6.8] kg; height: 1.8 [0.02] m; SA: 2.0 [0.1] m^2; BF%: 18.1 [2.9]%). All subjects gave their informed consent to participate and were medically screened to ensure that they had no pre-existing health conditions that could be result in injury during the study. Due to time and budget limitations, the two studies were separated by one year. Two males participated in both studies.

2.2. Test conditions

In both studies, each participant performed three, 3 h immersions in the Offshore Engineering Basin (OEB – NRC, St. John's, Newfoundland and Labrador) under the conditions listed in Table 1. The waves were generated using hydraulic drive wave makers located on one wall of the OEB, which provided a reproducible wave pattern representative of those found offshore. A 20-min Joint North Sea Wave Analysis Project (JONSWAP) wave spectrum was used in both studies based on data collected from a wave buoy deployed off the south east coast of Newfoundland, Canada. The subjects were oriented with their feet forward into the oncoming unidirectional waves.

For both studies, 11 speed-controlled custom built fans (SEA Ltd, Columbus, Ohio, USA) generated air flow (wind) controlled by a precision voltage reference to adjust wind speed at the location of the participant.

2.3. Equipment

Subjects wore a Transport Canada (TC) approved marine abandonment immersion suit (White's Manufacturing, Victoria, BC, Canada) certified to the standard CAN/CGSB-65.16-2005. This immersion suit was selected owing to latex wrist and neck seals that greatly reduced the chance of water leaking into the immersion suit. The underclothing provided to the subjects was standardized and based on that prescribed by CAN/CGSB-65.16-2005, similar to that prescribed in the majority of immersion suit standards tests. It consisted of wool socks, swimming trunks, cotton trousers, cotton undershirt, and a long sleeved cotton shirt. Swimming trunks were provided to the subjects so that they could enter a hot water bath (40 °C) to rewarm once the immersions were completed.

Skin heat loss and temperature were measured using heat flow transducers (Concept Engineering, Old Saybrook, CT, USA) attached to the subjects using porous adhesive tape to the following locations: right foot; left shin; right quadriceps; left abdominal; right pectoral; underside of right forearm; forehead; right calf; left hamstring; right lower back; left shoulder; and topside of the left forearm. These sites were chosen based on a similar protocol used by Ducharme and Brooks (1998), which was similar to the Hardy and DuBois (1938) modified 12 point system. The heat flow transducers were connected to self-contained data loggers (ACR Data Systems, Surrey, BC, Canada) that measured and recorded all 12 sensors once every 8 s.

2.4. Procedure

On the day of their immersion, participants changed into swimming trunks, were weighed, and self-attached an external bladder to enable in-test urination. This external bladder was attached via a condom catheter which prevented females from being eligible to participate. A research team member then attached the heat flow transducers and assisted the subjects in donning the rest of the underclothing. In Study 1, the subjects completely donned the immersion suit and proceeded to the testing area.

In Study 2, pre-wetting was performed similar to a condition in the experiment described by Tipton and Balmi (1996) as the authors reported a significant change in deep body temperature when only the torso was wetted. Our participants donned the immersion suit up to the waist while a research team member sprayed their torso (excluding the arms) with 500 mL of room temperature water uniformly across the front and back. This completely saturated the long sleeved shirt worn by the subjects, and any excess water runoff was caught by the immersion suit. Once wetting was complete, the participants finished donning the immersion suit, but left it unzipped and proceeded to the testing area.

2.5. Calculations

Body fat (BF) percentage was estimated using the Durnin and Womersley method (1969) from the sum of skinfold thickness from four sites: biceps; triceps, subscapular; and iliac crest.

Surface area (SA) of the participants was calculated using the following formula as described by Gehan and George (1970):