Prediction of Core Temperature During Prolonged Cold Water Immersion in Thermally Protected Men and Women

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ABSTRACT

Most cold-water thermoregulatory models are based on observations among subjects immersed without thermal protection. These models predict human physiologic responses and survival rates during sedentary cold-water immersion, but few models predict core temperature responses during cold water immersion in a thermally protected diver. Divers working in cold water while wearing neoprene wetsuits or dry suits to increase thermal insulation enjoy partial protection from the environment but the risk of hypothermia remains. The purpose of this exploratory analysis was to develop a preliminary model to predict core temperature responses during cold water immersion while wearing a 7mm wetsuit, hood, gloves, and boots. This model was based on subject morphometrics, water temperature (T_W), and immersion time (I_t). Data were aggregated from multiple studies and included 51 subjects completing 109 cold water immersion exposures ranging from 60-240 min in 10-25°C water. Subject's age, sex, height (cm), mass (kg), body surface area (BSA) (m^2) or body mass index (BMI), and estimated body fat (BF%) were entered into the model as potential variables to predict drop in core temperature during immersion. A step-wise reduction regression model was formed using these variables. The model was reduced until all remaining variables were significant to $p < 0.15$. The best fit model ($p < 0.001$) predicted core temperature drop as a function of BMI ($p = 0.03$), I_t ($p = 0.02$), T_W ($p < 0.001$), BF% ($p < 0.001$), and $I_t x T_W$ interaction ($p = 0.02$). A predictive model was also developed for the change in core temperature for the average male subject centered on the mean of each variable collected. Under this model, a male diver (24 y, BF = 13.5%, BMI = 26.0) in a 7mm wetsuit immersed in 15°C water would experience a decrease in core temperature of 0.55°C in 180 minutes. This could result in mild shivering and loss of dexterity. This novel analysis informs dive plans and provides recommendations for commercial and military divers exposed to prolonged cold-water dives in a 7mm wetsuit. During these dives, the risk of hypothermia is still present even with thermal protection. This analysis provides a foundation for similar models to be developed and begins to fill a gap in the current literature surrounding predictive cold-water immersion models. Future research should progress cold water thermoregulatory models by considering other thermal insulative ensembles and metabolic heat production.

1.0 INTRODUCTION

Physiologic and thermal responses to water immersion have been a continuous and expanding area of research for the better part of the last century. Cold water immersion (CWI) has been of particular interest for understanding hypothermia, survival rates, and its relevance to military warfare and training operations. It is well known that thermoregulation during CWI is strongly associated with water temperature (T_W) and exposure duration, as well as metabolic heat production, insulative and thermal protection [1], [2], [3]. Hypothermia during water immersion can lead to loss of motor and cognitive function, reduced peripheral blood flow and increased cardiovascular stress, shivering fatigue, and risk of drowning. Therefore, thermoregulation during CWI has been a vastly researched topic to prevent unfavorable outcomes.

To date, several mathematical models have been developed for use in predicting physiologic responses to immersion in cold water conditions including body heat balance, metabolic demands, shivering rates, core and skin temperatures, and survival outcomes [4], [5], [6], [7]. More recently, sex differences during cold stress have been examined which may lead to significant adjustments in thermal modelling to account for varying shivering and metabolic rates between men and women [8], [9]. Regardless, many lab-based studies directed towards prediction of hypothermic risk in cold water immersion and diving scenarios have not included thermal protection and insulation garments as a modifying factor despite the large impact on thermodynamics.

Controlled CWI exposures designed for military operations utilize wetsuits or drysuits depending on conditions [10], [11]. These military operations often require extended exposures and may be required to remain relatively static during immersion, which places a greater reliance on thermal protection to maintain body temperature in these conditions. While neoprene wetsuits are common among divers, the insulative effect on thermoregulation has proven difficult to study due to the water circulation between the suit and the skin [12]. Nevertheless, it has been shown that reductions in core temperature (T_C) are mitigated during immersion with a wetsuit and therefore permits greater exposure times [13], [14]. Thermal models have been used by the US Navy to simulate tolerance limits in cold waters and to aid in development of thermal protection garments [15]. Wetsuits increase survival time in cold water conditions, and accurately predicting tolerance time would benefit training and operational dive missions [16]. Current models however, are unable to use readily available anthropometrics in combination with insulative garments to predict thermal responses during prolonged CWI.

As it relates to military relevant CWI operations, the multifaceted effects of individual morphometrics, thermal protection, and exposure duration have not been fully addressed in thermal models. The inability to accurately account for thermal protection garments worn during immersion presents a challenge to dive planning operations and a gap in the current literature. The aim of this secondary analysis was to provide a preliminary model to predict T_C responses during CWI while wearing a 7mm neoprene wetsuit. This analysis is important for decision aid and dive planning operations in thermally stressful cold water conditions.

2.0 METHODS

2.1 Data Sources

This secondary analysis was performed with pooled data collected from five previous studies completed in our laboratory [17], [18], [19] (and unpublished work), all of which included CWI for 1-4 hr while wearing a 7 mm neoprene wetsuit, boots, gloves, and a hood during exposures. Fifty-one participants completed 83 CWI and 26 thermoneutral immersions ranging from 10-25˚C (Table 1). Raw data from these experiments included morphometrics (i.e., age, sex, height, body mass, calculated body surface area (BSA; m^2) [20] and body mass index (BMI; $kg \cdot m^{-2}$), estimated body fat percent (BF%), T_W, and T_C during the immersion protocol. All studies estimated body fat using body density determined from three-site skinfold measurements[21] [22]. Subjects were 24 ± 2 y, 76.3 ± 6.4 kg, and 174 ± 4 cm with BMI of / 25.2 ± 1.2 $kg \cdot m^{-2}$, calculated BSA of 1.9 ± 0.1 m^2, and estimated body fat percentage of 16.0 ± 3.4%. Participant characteristics for each study are provided in Table 2.

Table 1: Study protocols.

Study No.	Study Trial	Number of Immersions	Immersion Conditions			Immersion Position and Study Protocol	VO_{2peak}	Core Temperature Response	
			Duration (min)	Water Temp. (˚C)	Depth			Baseline T_C (˚C)	Final T_C (˚C)
1 [17]	A	12	60	25	HOWI 1.0 ATA	Seated rest – HOWI Dexterity testing at 15 and 45 min of immersion	n/a	37.2 (0.3)	36.9 (0.4)
	B	12	60	10				37.4 (0.1)	36.7 (0.4)
2 [19]	A	14	201 (11)	25	HOWI 1.6 ATA	Seated rest – HOWI Carotid body chemosensitivity testing during immersion	n/a	36.9 (0.3)	36.6 (0.5)
	B	14	204 (12)	15				37.0 (0.3)	36.7 (0.6)
3 [18]	A / B	18	240	10	SUBM 1.0 ATA	Seated rest – SUBM salt water (salinity: 23.1 g/L) breathing surface supplied air	46.4 (3.0)	37.1 (0.3)	36.8 (0.6)
4^a	A	9	240	20	HOWI 1.0 ATA	Seated Rest – HOWI Breathing surface supplied air OR Breathing 100% O2	45.5 (4.3)	37.1 (0.3)	36.7 (0.4)
	B	9	240	20				37.0 (0.3)	36.7 (0.4)
5^a	A / B / C	21	240	18	HOWI 1.0 ATA	Seated Rest	50.8 (5.3)	36.9 (0.2)	36.7 (0.3)
AVG	**-**	**109**	**190 (72)**	**17.6 (5.4)**	**-**	**-**	**47.6 (2.8)**	**37.1 (0.2)**	**36.7 (0.1)**

a: unpublished data; HOWI: head out water immersion; SUBM: submersion; data are mean (SD)

Table 2: Subject characteristics.

Study No.	Participants [Female]	Age (y)	Weight (kg)	Height (cm)	BMI (kg·m^{-2})	Body Fat (%)	BSA (m^2)
1 [17]	12 [6]	23 (2)	70.4 (12.4)	171 (10)	23.9 (2.5)	16.1 (6.4)	1.82 (0.2)
2 [19]	14 [0]	27 (4)	78.9 (8.1)	175 (6)	25.7 (1.9)	n/a	1.94 (0.1)
3 [18]	9 [0]	23 (1)	83.7 (7.0)	178 (8)	26.5 (2.0)	17.4 (5.0)	2.02 (0.1)
4[a]	9 [4]	25 (2)	68.7 (13.3)	169 (9)	24.0 (2.5)	19.3 (5.1)	1.78 (0.2)
5[a]	7 [0]	23 (2)	79.6 (10.4)	176 (8)	25.8 (2.4)	11.3 (3.6)	1.96 (0.2)
Average	51 [10]	24 (2)	76.3 (6.4)	174 (4)	25.2 (1.2)	16.0 (3.4)	1.9 (0.1)

a: unpublished data; data are mean (SD)

2.2 Study Protocol Variation

Participants in each study wore an appropriately sized 7mm wetsuit during immersion and all studies included a cold water condition (≤20˚C) while two studies [17], [19] also included a thermoneutral condition (~25˚C) previously determined in our lab to be thermoneutral in most subjects while wearing a 7mm wetsuit. Three of the five studies [17] were completed as a head out water immersion (HOWI) while sitting in an upright position in a chair immersed to the level of the clavicle. One study was completed in the same position in saltwater (salinity: 23.1 g/L) while completely submersed a few inches below the surface [18]. Another study was completed in the HOWI position in the wet portion of a hyperbaric chamber pressurized to a depth of 1.6 ATA [19]. During two studies, participants wore a full-face mask regulator (Ocean Technology Guardian, Ocean Technology Systems, Santa Ana, California) while breathing surface supplied air or 100% O_2, depending on the experimental condition [18]. During all other studies, subjects breathed room air with the exception of brief carotid body chemosensitivity testing using hypercapnic and hypoxic gases in one study [19]. Subjects sat with little movement during immersion. In one study, dexterity testing was completed 15 and 45 minutes into immersion which involved arm and hand movements and a brief (~3 min) exposure of the face to the cold water [17]. During all studies, participants exited the water briefly every 60 minutes to void before resuming immersion or submersion.

2.3 Data Collection

Core temperature was measured with an ingestible capsule (CorTemp, HQ Inc, Palmetto, Florida) taken 6-8 hr prior to the visit. T_C change from baseline (ΔT_C) was calculated as the difference between final T_C and T_C at minute 0 of immersion. Calculated data (ΔT_C) stratified by T_W and immersion duration are presented in Figure 1.

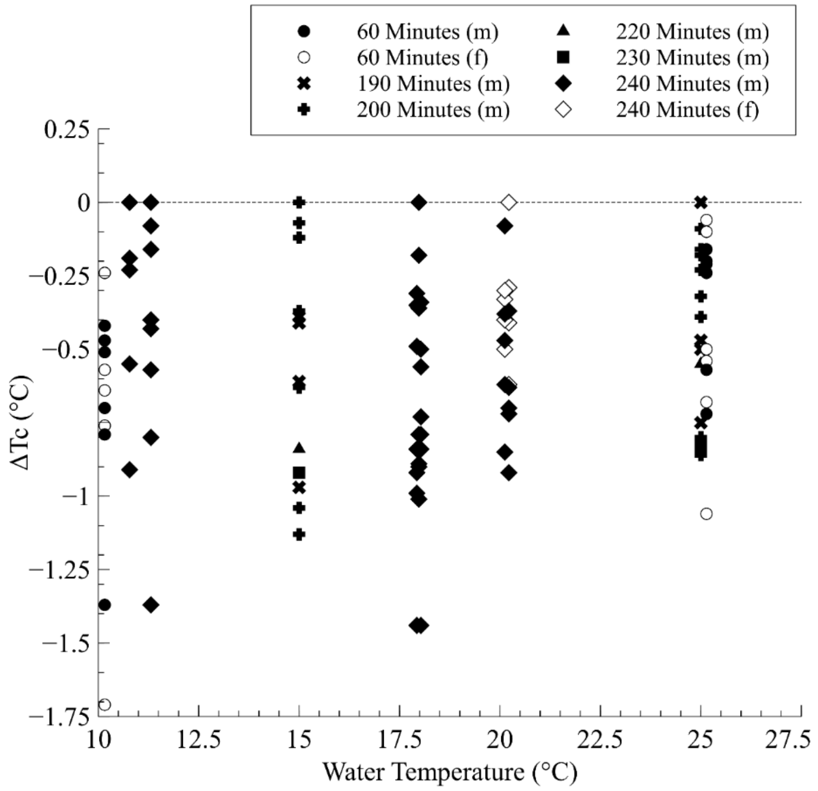

Figure 1: Change in core temperature (ΔT_C) stratified by water temperature and immersion time (symbols in legend) for each immersion trial for each subject (male: filled; female: open).

2.4 Model Development and Validation

Two models were developed with ΔT_C as the primary outcome variable using either BSA (Eq. 1) or BMI (Eq. 2) as predictors. Since BSA and BMI use similar morphometrics to compute, use of one or the other, but not both, were preferred for the final model and two equations were developed using the same regression analysis. Other variables of interest were sex, age, height, mass and BF% as reported in each study, as well as immersion time (I_t), T_W, and the interaction of I_t and T_W ($I_t x T_W$). The prediction equations were written as:

$$\Delta T_C\ (^{\circ}C) = a + b(BSA) + c(I_t) + d(T_W) + e(BF\%) + f(I_t x T_W) \qquad \text{Eq. 1)}$$

$$\Delta T_C(^{\circ}C) = u + v(BMI) + w(I_t) + x(T_W) + y(BF\%) + z(I_t x T_W) \qquad \text{Eq. 2}$$

2.4.1 *k*-Fold Cross-Validation

Internal model validation was performed by k-fold cross-validation (k=3).[20] Data was randomly allocated to three groups (group 1: n=34, obs=41; group 2: n=27, obs=30; group 3: n=33, obs=38). Differences between groups were analysed using a one-way analysis of variance (ANOVA) test. These groups did not differ by age ($p = 0.58$), height ($p = 0.87$), mass ($p = 0.85$), BMI ($p = 0.72$), BF% ($p = 0.98$), nor BSA ($p = 0.85$). Reduced models were fit to two of the groups (prediction subset) and the remaining group was used to evaluate the model (test subset). This process was repeated three times so that every group was used as the test subset once.

2.4.2 Statistical Analyses

Results are reported as mean ± standard deviation (SD). All statistical analyses were run using SAS (SAS OnDemand for Academics, SAS Institute Inc., New York NY). Alpha level was set to 0.05 unless otherwise noted. Study data were visually inspected for consistency between datasets and screened for askew data points. Additionally, linearity, normality, and constant variance assumptions were confirmed using Studentized residual and Q-Q plots. A mixed-effects model was used to develop the prediction equations, allowing for a clustering effect (random intercept) for subjects that repeated multiple conditions. Full equations were reduced in a step-wise manner until all remaining variables were significant to $p < 0.15$. Coefficients from the subset analyses were used to calculate predicted ΔT_C in the test subset. Predicted and actual ΔT_C were then evaluated for weak ($r < 0.30$), moderate ($r = 0.30\text{-}0.60$), or strong ($r > 0.60$) agreement with Pearson correlation coefficients.

3.0 RESULTS

3.1 BSA-Based Equation

The reduced BSA model included BSA ($p = 0.03$), I_t ($p = 0.03$), T_W ($p < 0.001$), BF% ($p < 0.001$), and the $I_t x T_W$ interaction ($p = 0.03$). Validation showed moderate to strong correlations to actual ΔT_C (Iteration 1: $r = 0.39$, $p = 0.03$; Iteration 2: $r = 0.69$, $p < 0.001$; Iteration 3: $r = 0.57$, $p = 0.006$). The overall model fit to the entire dataset ($p < 0.001$) resulted in the BSA-prediction equation (Eq. 3):

$$\Delta T_C\ (^{\circ}C) = -2.7133 + 0.5625(BSA) + 0.00352(I_t) + 0.03312(T_W) + 0.03179(BF\%) - 0.000188(I_t x T_W) \qquad \text{Eq. 3)}$$

3.2 BMI-Based Equation

The reduced BMI model included BMI ($p = 0.03$), I_t ($p = 0.02$), T_W ($p < 0.001$), BF% ($p < 0.001$), and $I_t x T_W$ interaction ($p = 0.02$). Validation showed moderate to strong correlations to actual ΔT_C (Iteration 1: $r = 0.40$, p = 0.02; Iteration 2: r = 0.57, p = 0.002; Iteration 3: r = 0.63, p = 0.002). The overall model fit to the entire dataset ($p < 0.001$) resulted in the BMI-prediction equation (Eq. 4):

$$\Delta T_C\,(^{\circ}C) = -2.694 + 0.04267(BMI) + 0.00366(I_t) + 0.03373(T_W) + 0.03015(BF\%) - 0.000198(I_t x T_W) \qquad \text{Eq. 4)}$$

3.3 Application

During a predicted 3 h submersion in 15°C T_W, both models (Eq. 3 and 4) predict a ΔT_C of -0.55°C for the average male (age: 24 y, height: 176.3 cm, body mass: 80.8 kg, BSA: 1.97 m^2, BMI: 26.0, BF%: 13.5%), whereas the true average ΔT_C was -0.52 ± 0.36°C. Figure 2 shows differences between predicted and measured ΔT_C across the range of observed ΔT_C values, T_W and I_t, for both models.

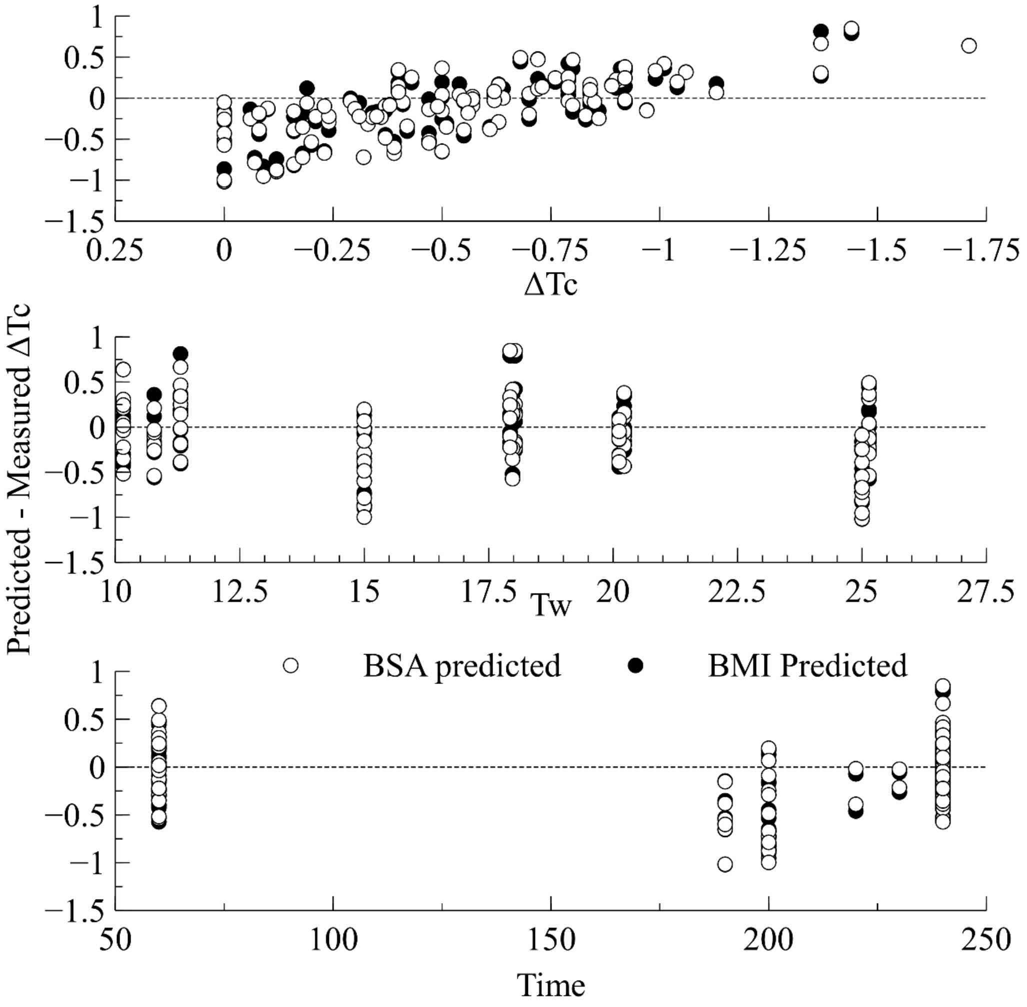

Figure 2: Differences between predicted and measured change in core temperature (ΔT_C) over observed ΔT_C (*top*), water temperature (T_W: *middle*), and immersion time in min (*bottom*) for BSA-based (open) and BMI-based (filled) equations. Dotted line is line of zero difference.

4.0 DISCUSSION

The results from these analyses provide two models to predict ΔT_C in water temperatures between 10˚C and 25˚C for up to four hours of seated immersion. Both models (Eq. 3 and 4) met criteria for statistical acceptance and agreement during each round of validation testing. To the best of our knowledge, this is the first analysis to model predictions for ΔT_C during CWI and while wearing a 7mm wetsuit.

There was a weaker relationship between predicted versus measured values when the decrease in core temperature was smaller than ~0.3˚C from baseline (Figure 2). Surprisingly, the incidence of such minimal core temperature drops was not related to immersion water temperatures or duration as $\Delta T_C \leq 0.3$˚C seemed to be equally distributed across trials in T_W ranging from 10-20˚C (Figure 1). Potential explanations for this include variability in subject's morphometrics, particularly percent body fat, [2], [24] the brief egress during immersions greater than 1 hr which likely caused fluctuation in shivering rate, and differences in magnitude of physiological response to cooling (i.e., metabolic-insulative versus insulative-hypothermic responses) [25].

In agreement with previous studies' findings, it is expected that body fat has a large influence in the current models used for Tc prediction during cold stress [2], [26]. In this study, participants had regular BSA, slightly elevated BMI, and a healthy amount of body fat, which generally represents a US Navy diver population,[11], [27] but may not fully characterize other diver populations that fall outside of this range. Previous work has shown that models comparing normal and low body fat groups may overpredict T_C responses in those with low but not normal body fat [28]. In unprotected subjects, the role of body fat in CWI prediction models is a critical variable for improving metabolic rate predictions.[29] Similar to the current study, the best fit models to predict shivering heat production without thermal protection during immersion in waters as low as 8˚C included body fat and BMI, highlighting the morphometric variations in these scenarios [26].

All data sets examined in this analysis used seated resting conditions and did not consider the contribution of exercise which could be expected to blunt the drop in core temperature. In unprotected men, the rate of core temperature reduction in the resting diver is greater compared to an active diver at any given water temperature up to 20˚C [5]. It has been suggested that lower limb, but not upper limb, movements also blunt core temperature drop [30], [31]. However, in extremely cold water (10.5˚C) without thermal protection, swimming increases heat production and also increases the rate of core temperature cooling, but this has not been confirmed in thermally protected subjects [32]. In thermally protected subjects, increased movement of water across the body may increase convective heat loss which could augment core temperature loss, and it is unlikely that the metabolic heat produced during exercise would overcome the power needed to maintain core and skin temperatures in waters ≤15˚C [33]. Regardless of thermal protection, current models for sedentary exposures cannot appropriately predict thermoregulation during exercise in cold water[34] and incorporating exercise metabolism would be a valuable addition to this prediction equation.

From the current data, divers wearing a 7mm wetsuit in cold water as low as 10˚C will maintain T_C within a safe limit for prolonged dives (up to 4 hours). However, it is important to note that the average core temperature change of ~0.5˚C in 15˚C water likely reached the threshold of the onset of shivering in resting subjects, which is approximately 36.5˚C [31]. Skin temperature was not recorded in the majority of the studies included here, but near maximal vasoconstriction would be expected in water temperatures between 10-20˚C while wearing a 7mm wetsuit [35]. Maximal vasoconstriction of the periphery provides the largest insulative potential of the tissue, and once reached the body will rely more on metabolic heat production, although the intensity and timing of this response would differ between subjects [2], [36]. This would also be expected to diminish dexterity, reduce blood flow, and may impair cognitive function, further limiting dive operations and safety [17], [37].

Similar studies examining thermal responses during prolonged cold water immersion have shown that thermal protection safeguards core temperature and sustains exposure times. A study evaluating Navy

Special Warfare Divers and concluded that when thick neoprene wetsuits are worn (20mm over the torso and 10mm over the hands and feet), core temperature may be sustained for up to 6 hours in 5˚C water [11]. Average core temperature change during submersion in the mentioned study was -0.7˚C despite extremely thick thermal protection, but a 53% increase in metabolic rate likely slowed this rate of decline. Similar prolonged dives in 18˚C and 10˚C water have shown that thermal protection is efficient to maintain core temperature above lower medical limits (~36˚C) but when extremity temperatures are considered, the thermal protection provided would not maintain operational efficiency (e.g., manual dexterity) [10]. Core temperature change in these conditions was approximately -1.0˚C. Without thermal protection, developed models can accurately predict survival time, T_C, skin temperature and maximal metabolic rates for those immersed in waters as low as 8˚C. However, as shown briefly in data provided by an accidental capsize, survival time when wearing a wetsuit in approximately 16˚C water could not be appropriately predicted, as noted by the authors [6], [7]. These studies highlight the potential application of the thermal model presented here, which should be further developed to include additional wetsuit thicknesses, increased depths, and physical activity over a wider range of exposure conditions. This would then be beneficial to finding operationally relevant tolerance limits when working in the field.

4.1 Considerations and Limitations

This preliminary work has aimed to set the groundwork for future model development of changes in core temperature during cold water immersion in thermally protected divers. To the best of our knowledge, no model currently exists to examine this relationship, and therefore external validation was not possible and remains a limitation of the analysis. The dive protocols used varied somewhat in activity, position, immersion time, and water temperature which may have increased response variability to these exposures and limited internal validity, but would have enhanced external validity as it could be generalized to a larger number of real-world scenarios. This model was fit using a linear regression analysis, where a non-linear relationship was not explored herein. The relationship between T_C, T_W, and I_t may in fact present a non-linear association, especially once metabolic or shivering rates, heterogeneous thermal protection (i.e., increased core versus peripheral insulation), or increased depth is introduced. Finally, all body fat measurements in the included studies were estimated from body density and therefore is limited by this method compared to more accurate assessments.

4.2 Conclusions

This study has provided two models useful to predict core temperature drop while immersed in cold water using readily available subject variables, and while wearing a 7mm wetsuit. Current CWI models are insufficient for operational exposures and dive plan management since they cannot account for adequate thermal protection when planning for cold water exposures. These models could be further developed to take into consideration varying thermal protection garments, decreased wetsuit insulative protection with increased depth, and increased metabolic rates due to shivering or exercise.

5.0 REFERENCES

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