International Journal of Sports Physiology and Performance, 2025, 20, 213-223
https://doi.org/10.1123/ijspp.2024-0100

Human Kinetics
ORIGINAL INVESTIGATION

Manual Dexterity in Open-Water Wetsuited Swimmers: A Cohort Crossover Study

William J. Morton,[1,2,3] Jørgen Melau,[2,4] Roar A. Olsen,[5,6,7] Ole Martin Løvvik,[8,9] Jonny Hisdal,[2,3] and Signe Søvik[1,3]

[1]Department of Anesthesiology and Intensive Care, Akershus University Hospital, Lørenskog, Norway; [2]Department of Vascular Surgery, Oslo University Hospital, Oslo, Norway; [3]Institute of Clinical Medicine, University of Oslo, Oslo, Norway; [4]Norwegian Armed Forces, Joint Medical Services, Sessvollmoen, Norway; [5]Norwegian Swimming Federation, Oslo, Norway; [6]Fet Svømmeklubb, Fetsund, Norway; [7]Oter'n, Gan, Norway; [8]SINTEF Materials Physics, Oslo, Norway; [9]Department of Physics, Center for Materials Science and Nanotechnology, University of Oslo, Oslo, Norway

Purpose: Laboratory studies have demonstrated that manual dexterity decreases with increasing cold, which may adversely affect performance. Dexterity may be impaired by cooling of the hand, cooling of the lower motor neurons, and cognitive impairment. Wetsuits are commonly used in open-water swimming and are mandated in some situations. This study investigates the effects of cold-water wetsuited swimming on dexterity. ***Methods:*** Five male and 4 female trained swimmers were recruited for this cohort crossover study. Following dual-energy X-ray absorptiometry scans to determine body composition, they swam in a freshwater lake on 7 occasions with water temperatures between 24.5 °C and 8.4 °C. Dexterity was measured preswim and postswim with a "nut–washer–bolt assembly time test" and cognition with a Stroop test. Core and peripheral body temperatures were continuously monitored. Effects were analyzed by linear mixed-model regression. ***Results:*** Pre–post swim difference in time to complete the nut–bolt assembly increased as water temperatures decreased (1.0 s, 95% CI, 0.5–1.5 per 1 °C, $P < .0001$; $R^2 = .456$), to a maximum of 14.7 seconds (95% CI, 3.3–26.0). This represented a 47.5% increase in assembly time from 24.5 °C to 8.4 °C, which we consider to be of practical significance. Decreased dexterity was associated with decreased forearm and scapular temperature and decreased cognitive function. Body composition did not affect dexterity, cognitive function, or body temperature during swims. Water temperature did not affect swim speed. ***Conclusions:*** Despite the use of wetsuits, manual dexterity decreased with cold-water swimming. Swimmers, triathletes, and event organizers should consider the implications for safety, performance, and equipment utilization.

Keywords: swimming, cold, cognition, body composition

The reasons for swimming in cold water can be divided into 3 categories: for survival, for professional activities, and for sport and recreation. The ability to use one's hands effectively to manipulate tools or perform tasks essential to survival is of critical importance to the first 2 categories. Golden and Tipton[1] state that survival may be divided into functional survival, during which the subject may still influence their prognosis, and passive survival, during which they may not. Manual dexterity is of primary importance in determining at which point one transitions from functional to passive survival. Although the biomechanics of swimming lie beyond the remit of this paper, swimming efficiency is dependent on the orientation of the hands and fingers to provide propulsion.[2] Consequently, dexterity is also of consequence for recreational swimmers.

Manual dexterity can be defined as skilled behavior involving the hands and may be thought of as being produced through a series of steps.[3] The precise positioning of the fingers is controlled by 20 forearm and 21 hand muscles on each side, innervated by lower motor neurons.[3] The desire to move the hand is actuated in the motor cortex and posterior parietal cortex where it is transmitted via the upper motor neurons and spinal cord, which may also be innervated by corticomotorneuronal cells for automatized processes, such as hand position in trained swimmers.[3] Simultaneously, tactile feedback from the skin, proprioception, muscle spindles, and visual input allow for refinement and correction of dexterous movement.[3] Dexterity can be impaired by compromise at any point on the pathway. Of relevance in cold-water swimmers are cooling of the hand muscles and the skin overlying them, impairment of the lower motor neurons due to cooling (particularly of the exposed ulna nerve as it passes posteriorly to the medial epicondyle of the elbow),[4] and mental confusion due to central hypothermia and the cognitive load of cold-water exposure.[5]

The fingers and hands have the largest surface area to volume ratio of any body part[6]; therefore, their temperature is rapidly affected by cold-water immersion. Laboratory studies have demonstrated that manual dexterity decreases with decreasing hand skin temperature.[7–10] Heus et al[11] demonstrated that dexterity is

---

Melau https://orcid.org/0000-0002-3860-3988
Løvvik https://orcid.org/0000-0002-4169-1544
Hisdal https://orcid.org/0000-0002-0224-7854
Søvik https://orcid.org/0000-0003-4524-2268
Morton (william.james.morton@ahus.no) is corresponding author, https://orcid.org/0000-0002-3225-6321

impaired with a fall in skin temperature, nerve temperature, and muscle temperature below 15 °C, 20 °C, and 28 °C respectively. Ofir et al[12] found an approximately 30% increase in the time required to assemble a shackle system after a laboratory 2-hour fin swim immersion in 20 °C, 18 °C, and 16 °C water, irrespective of the water temperature. Conversely, other laboratory studies have found that water temperature affects finger temperature, which in turn determines dexterity.[9,13] Finger and hand temperature is a major determinant of dexterity, although it is unclear if the reduction in dexterity is dependent solely on maximum temperature reduction or the cold exposure "dose," that is, the area under the time–temperature curve.

The motoric and sensory innervations for fine hand movements are primarily conducted by the radial and ulnar nerves, and due to the ulna nerve's exposure at the elbow, it is liable to be affected by immersion in cold water. There is a semilogarithmic relationship between decreasing temperature and decreasing nerve conduction velocity.[14] Laboratory immersion of the lower leg in circa 10 °C water increased latency and compound action potential of the tibial nerve as well as the amplitude and duration in the sural nerve.[15] These changes in nerve conduction velocity, amplitude, and latency result in decreased muscle stimulation.[16] This is compensated for with an increased recruitment of muscle motor units above 20 °C and an earlier activation of fast muscle motor units below 20 °C, which results in an increased electromyography for a given workload with the price of decreased endurance.[17] In laboratories, these changes result in impaired finger dexterity at low temperatures, probably due to agonist–antagonist muscle group interactions[18] and reduced proprioception,[19] although these interactions may be preserved for well-practiced skills.[20] The effects of local neuronal cooling on dexterity has not previously been investigated in active cold-water swimming.

In laboratory studies, the cognitive impacts of passive cold-water immersion are due not solely to cooling but also to the effects of distraction and result in decreased attention, executive function, speed of processing, and memory.[5] In their recent systematic review of cold exposure on cognitive performance, Falla et al[5] identified 10 cold-water immersion studies, of which 9 showed cognitive function decline during or after nonexercising immersion. Cognitive function has however been shown to be improved after a 20-minute swim in 30 °C water, with a reduction in reaction time of 3% to 4%.[21] Such exercise induced improvement in cognitive function appears to be reversed in cold-water temperatures.[22] The effects of a decrease in core body temperature appear to be dose related, with a decrease in complex cognitive task functions but relatively preserved performance for simple cognitive tasks.[23]

Few studies have investigated the effects of exercising in cold water on cognitive function. Ofir et al[12] investigated the thermal protection of 2- to 3-mm wetsuits during a 2-hour SCUBA swim immersion at 20 °C, 18 °C, and 16 °C and found no significant difference between preswim and postswim cognitive tests, including a modified Stroop test. In a laboratory study of simulated triathlons at 10 °C to 16 °C of water temperature, Saycell et al[24] found that lower water temperature increased errors during a subsequent technical bike course. Swims below 10 °C have rarely been investigated. Knechtle et al[25] reported 2 swimmers who swam for 23 and 42 minutes in 4 °C water; both experienced profound declines in cognitive function with severe disorientation and inability to recall names of family members. In a crossover study, Waag et al[26] found that exercise better protected against hypothermia than static shivering in 6-hour survival suit immersion at 3.6 °C water. There is however a deficit in knowledge concerning the effect of cold open water swimming on cognitive function.

In the 2022 financial year, global wetsuit sales reached a valuation of US$ 1.72 billion[27] with the implication that a significant proportion of cold-water immersions occur in wetsuits. Indeed, use of wetsuits is mandated below 18 °C by World Aquatics (formerly Fédération Internationale de Nataion)[28] and <15.9 °C by the World Triathlon (formerly International Triathlon Union).[29] The insulating properties of wetsuits differ substantially from swim wear, normal clothing,[30] and drysuits[31] and consequently warrant investigation.

To the best of our knowledge, no previous study has investigated the association between manual dexterity and cold open water swimming, in which the continuous use of the hands may result in a relatively preserved dexterity. The aim of this paper is to investigate how the duration and ambient water temperature of cold water wetsuited swimming affects manual dexterity.

Methods

Subjects

The study was performed according to the institutional ethics requirements of the Institute of Clinical Medicine at the University of Oslo and was endorsed by the Norwegian Swimming Federation's research office (Norges Svømmeforbund). Approval for data security and handling was obtained from the Data Protection Officer at Oslo University Hospital (reference # 20/09179). The study was conducted in accordance with the current revision of the Declaration of Helsinki.

Five male and 4 female trained or highly trained swimmers from Lillestrøm county in Norway were recruited.[32] They regularly participated in open water swimming activities organized by their clubs. Following written informed consent and a medical examination, they were invited to participate in the study as part of their scheduled training. Baseline anthropomorphic measurements (Table 1) including weight, height, and dual-energy X-ray absorptiometry (DXA-scan) (Lunar Prodigy densitometer, GE Medical Systems) were recorded before the first swim. Body mass index (BMI) was calculated by weight in kilograms divided by squared height in meters.

Design

This cohort crossover study was designed to evaluate manual dexterity with wetsuited swimming in cold water.

Methodology

The test period was June to October 2020 and included swims on 7 occasions with water temperatures between 24.5 °C and 8.4 °C. Details regarding water temperature, weather conditions, swim distance, and duration are given in Table 2. The swimmers used their own well-fitting wetsuits, silicone swim hats, and tow-buoys (Table 1). Swimmers were free to supplement their insulation with neoprene hats, gloves, and booties at their own discretion (Figure 1). The swims were conducted according to the swim clubs training program with the individual swimmer determining the duration and distance of their swim. Safety support was provided by a paramedic present at all swims. Swim distance was measured by the swimmers' own Global Positioning System-enabled watches.

Manual dexterity was measured immediately before and immediately after the swim using a standardized test in which participants assembled 2 separate and different-sized pairs of bolts,

Table 1 Anthropomorphic and Wetsuit Data

Swimmer	Sex	Age, y	Height, m	Weight, kg	Lean mass, kg	Fat mass, kg	Total body fat, %	Body mass index, kg/m^2	Wetsuit, mm
1	Male	45.9	1.83	79.2	57.9	18.0	23.8	23.6	Blue Seventy (1.5–5)
2	Female	52.1	1.68	68	41.1	24.0	36.9	24.1	Orca (3)
3	Male	50.7	1.76	81	60.8	17.8	22.6	26.3	Zoggs (1.5–3)
4	Female	47.9	1.81	67.1	43.7	21.0	32.4	20.5	Zoggs (1.5–3)
5	Male	47.7	1.83	117.3	67.6	45.7	40.3	35.0	Zoot (3–5)
6	Male	47.7	1.89	88.4	67.1	17.9	21.1	24.7	Zoot (3–5)
7	Female	22.7	1.69	74.8	50.5	21.5	29.9	26.2	Blue Seventy (1.5–5)
8	Female	48.6	1.73	65.9	51.2	13.0	20.2	22.1	Huub (3–5)
9	Male	49.3	1.85	90.5	62.7	24.6	28.2	26.4	Zoot (3–5)
Mean (SD)	5:4 ♂:♀	45.9 (8.43)	1.785 (0.071)	81.3 (15.37)	55.9 (9.23)	22.6 (9.23)	28.4 (6.78)	25.4 (3.91)	

Table 2 Environmental Conditions and Swim Metrics

Swim date (2020)	Swim start time	Water temperature, °C	Air temperature, °C	Relative humidity, %	Wind speed, m/s	Swim distance, m, mean (95% CI)	Swim duration, min, mean (95% CI)
June 1	18:41	20.6	27.7	32.2	2.1	2071 (1726 to 2416)	56.9 (51.3 to 62.5)
June 18	18:17	24.5	28.1	37.3	1.1	2512 (1960 to 3065)	62.1 (48.9 to 75.3)
Sep 3	18:33	16.7	16.4	66.4	1.6	1907 (1435 to 2379)	49.1 (41.2 to 57)
Sept 17	18:27	14.0	11.8	43.2	0.0	1702 (1265 to 2138)	45.6 (38.1 to 53.1)
Oct 1	18:47	12.1	10.6	80.9	1.6	1480 (1158 to 1803)	39.8 (34 to 45.5)
Oct 8	19:01	11.6	10.5	85.3	0.5	1601 (1186 to 2016)	44.9 (38.1 to 51.6)
Oct 18	16:53	8.4	7.2	41.4	1.6	1179 (978 to 1381)	31.9 (26.9 to 36.8)

Note: Data from 9 swimmers doing repeated self-paced self-limited swims in fresh open water.

washers, and nuts. Their assembly time was recorded with a stopwatch. The nuts and bolt assembly test has been used in several studies.[10,11,33] Preswim and postswim testing was conducted in a standing tent to minimize the impact of environmental conditions.

During the swim, skin sensors located on the left forearm and right scapula were used to record skin temperature every minute (iButton, Maxim Integrated Products Inc). An ingestible pill was rectally self-inserted 15 minutes prior to immersion (e-Celsius, BodyCAP) and measured the swimmers' core temperature every minute.[34] The data were downloaded using the e-Viewer Performance monitor from the same company.

Cognitive function was assessed with a Stroop test,[35] which is a commonly used and validated neuropsychological assessment in the investigation of cold exposure.[5] The Stroop test requires the test subject to name colors written in either the congruent or incongruent ink color, for example, the correct response is "red" to the word "blue" if printed in red ink. The Stroop test has an "off" state in which text and color are congruent and an "on" state in which they are incongruent. The Stroop test was administered with a validated[36,37] smart phone application (HindSoft Technology Pvt Ltd, EncephalApp software) in which large screen "buttons" negated any potential changes in dexterity. The time to correctly complete 5 runs of the test was recorded, and the difference between the preswim and postswim times was calculated.

Swims occurred in a fresh water lake. Water temperature was measured at a depth of 50 cm with a calibrated temperature monitor (Fluke 51, Fluke Corporation). The air temperature, humidity, and wind speed were determined with a calibrated weather meter (Kestrel 5400 Heat Stress Tracker, Kestrel instruments). After each swim, participants also reported on wetsuit fit and subjective effects of water temperature using a structured questionnaire with open-ended questions.

Statistical Analysis

Based on a previous study by our group,[33] sample size calculations showed that a minimum of 9 participants was required to detect a fall in core temperature of 0.1 °C. To ensure sufficient test strength and opportunity for regression analyses, the participants had to complete at least 6 swims, each under different temperature conditions. Raw data were loaded in Excel (Microsoft Excel for Mac, Version 16.19, Microsoft) and subsequently analyzed using JMP

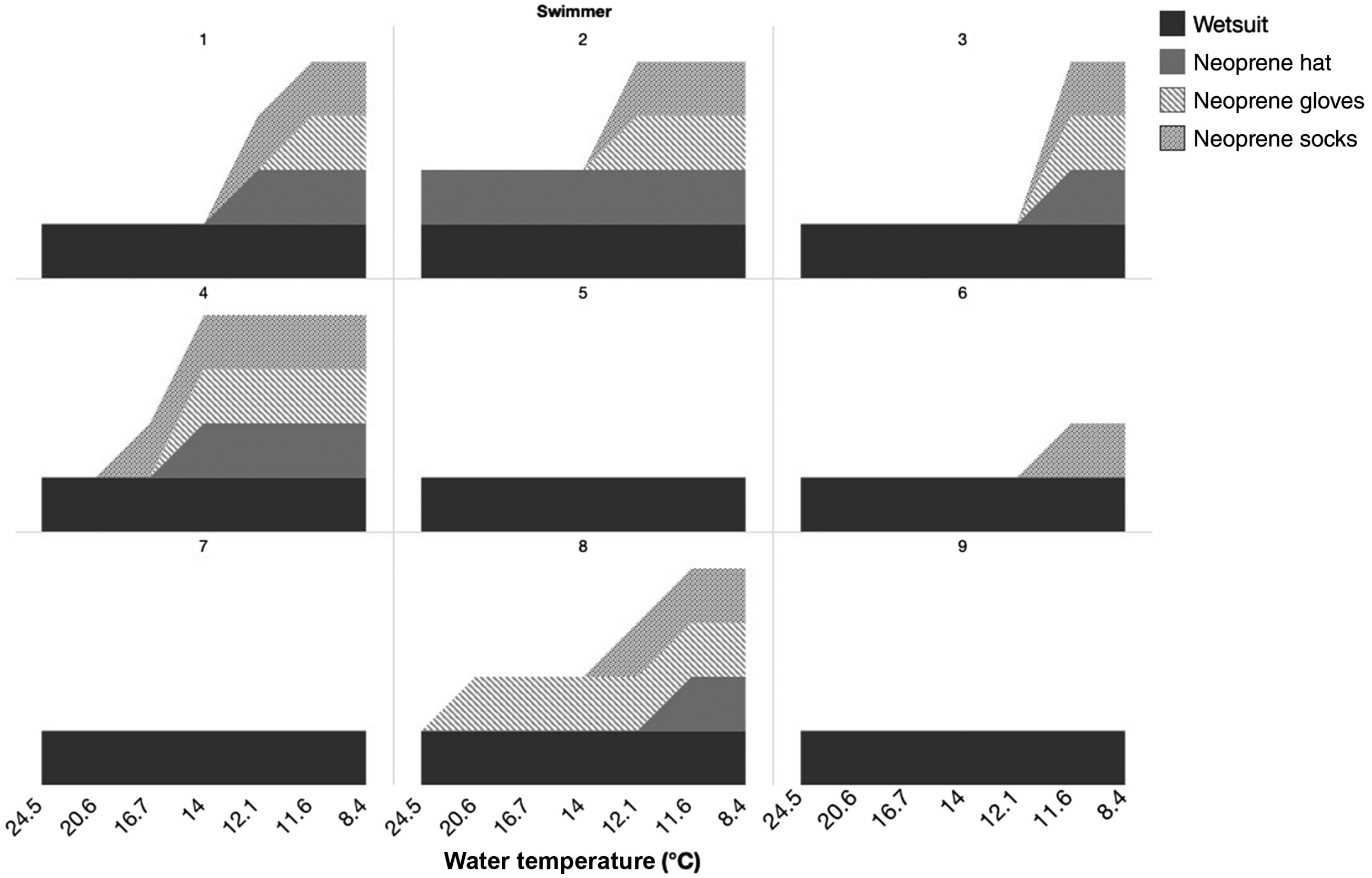

Figure 1 — Auxiliary insulation by swimmer and water temperature. Number indicates swimmer number.

Pro 17.0.0 (JMP Statistical Discovery LLC). Values are mean (95% CI) unless otherwise specified. Normality was assessed with the Shapiro–Wilk test. Effects of water temperature were analyzed using mixed-model linear regression with the subject as the (repeated) random factor. Statistical significance was determined by convention to have a null hypothesis *P* value of <.05.

Variables for repeated-measure analysis were chosen by purposeful selection[38] of factors suspected to influence the outcome (eg, for core temperature: water temperature, swim speed, and BMI). The model was then selected by changing the correlated variables, as determined by Pearson correlation, using Akaike information criteria to identify the model with the best penalized log-likelihood.[39]

Results

Of the 9 swimmers, 7 swimmers completed all 7 swims. Swimmer 6 did not swim October 1st (water temperature 12.1 °C) and swimmer 8 did not swim September 3rd (water temperature 16.7 °C).

Manual dexterity decreased with decreasing water temperature, indicated by increased difference in preswim versus postswim time to complete the nut–bolt assembly (Table 3). The estimated effect was 1.0 second (0.5–1.5) increased assembly time post swim per 1 °C decline in water temperature ($R^2 = .456$; $P < .0001$; (Figure 2). The mean difference in nut–bolt assembly time for all swims was 7.0 seconds (4.1 to 9.9), reaching a maximum of 14.7 seconds (3.2 to 26.0) at 8.4 °C.

An increase in nut–bolt assembly time was associated with the following:

1. Minimum temperature of the left forearm (1.2 s [0.6–1.8]) increase per 1 °C decline ($R^2 = .450$; $P < .0001$)
2. Minimum right shoulder temperature (1.2 s [0.7–1.6]) increase per 1 °C decline ($R^2 = .460$; $P < .0001$)
3. Increase in Stroop score (0.24 s [0.0 to 0.5]) increase per score difference ($R^2 = .23$; $P = .087$; Figure 3).

Nut–bolt assembly time difference was not statistically associated with core temperature, swim duration, swim speed, BMI, or total body fat percentage.

The possibility of a learning effect on the preswim nut–bolt assembly time was analyzed with a superiority test (powered to detect a difference of 1 s) that revealed that, compared with the last test (October 18), there was an improvement in performance from the first test (June 1st, $P = .007$) but not any subsequent test (June 18, $P = .4316$; September 3, $P = .2357$; September 17, $P = .2673$; October 1, $P = .3604$; October 8, $P = .1053$). We therefore found a learning effect between the first 2 swims (mean difference 9.00 s; 95% CI, 1.6 to 16.4; $P = .018$), but not with any subsequent swims.

A decrease in core temperature was not related to water temperature ($R^2 = .008$; $P = .5113$; Table 4). However, despite the lack of association between water temperature and a decrease in

Table 3 Dexterity Versus Water Temperature in Wetsuited Freshwater Swimmers

Water temperature, °C	Preswim Nut–bolt assembly time, s, mean (95% CI)	Postswim Nut–bolt assembly time, s, mean (95% CI)	Nut–bolt assembly time Difference, s, mean (95% CI)	*P* (SE)
24.5	28.3 (22.5 to 34.1)	29.7 (22.6 to 36.7)	1.3 (–3.7 to 6.49)	.559 (2.186)
20.6	37.3 (30.6 to 44.1)	36.8 (28 to 45.5)	–0.6 (–7.5 to 6.4)	.859 (3.033)
16.7	30.4 (23.8 to 37.1)	35.1 (28.5 to 41.7)	4.7 (0.6 to 8.7)	**.029** (1.748)
14.0	30.1 (25.3 to 34.8)	38.2 (32.1 to 44.4)	8.2 (1.9 to 14.4)	**.016** (2.707)
12.1	29.1 (21.2 to 37)	43 (28.2 to 57.8)	13.9 (3 to 24.9)	**.02** (4.633)
11.6	32.6 (25.4 to 39.8)	42.4 (30.6 to 54.2)	9.8 (–1.8 to 21.3)	.086 (4.889)
8.4	26.7 (23.2 to 30.1)	41.3 (28.9 to 53.7)	14.6 (3.2 to 26)	**.019** (4.821)

Note: Data from 9 swimmers doing self-paced self-limited swims in fresh open water (see Table 2). Statistically significant differences in postswim versus preswim nut–bolt assembly time are marked with bold font.

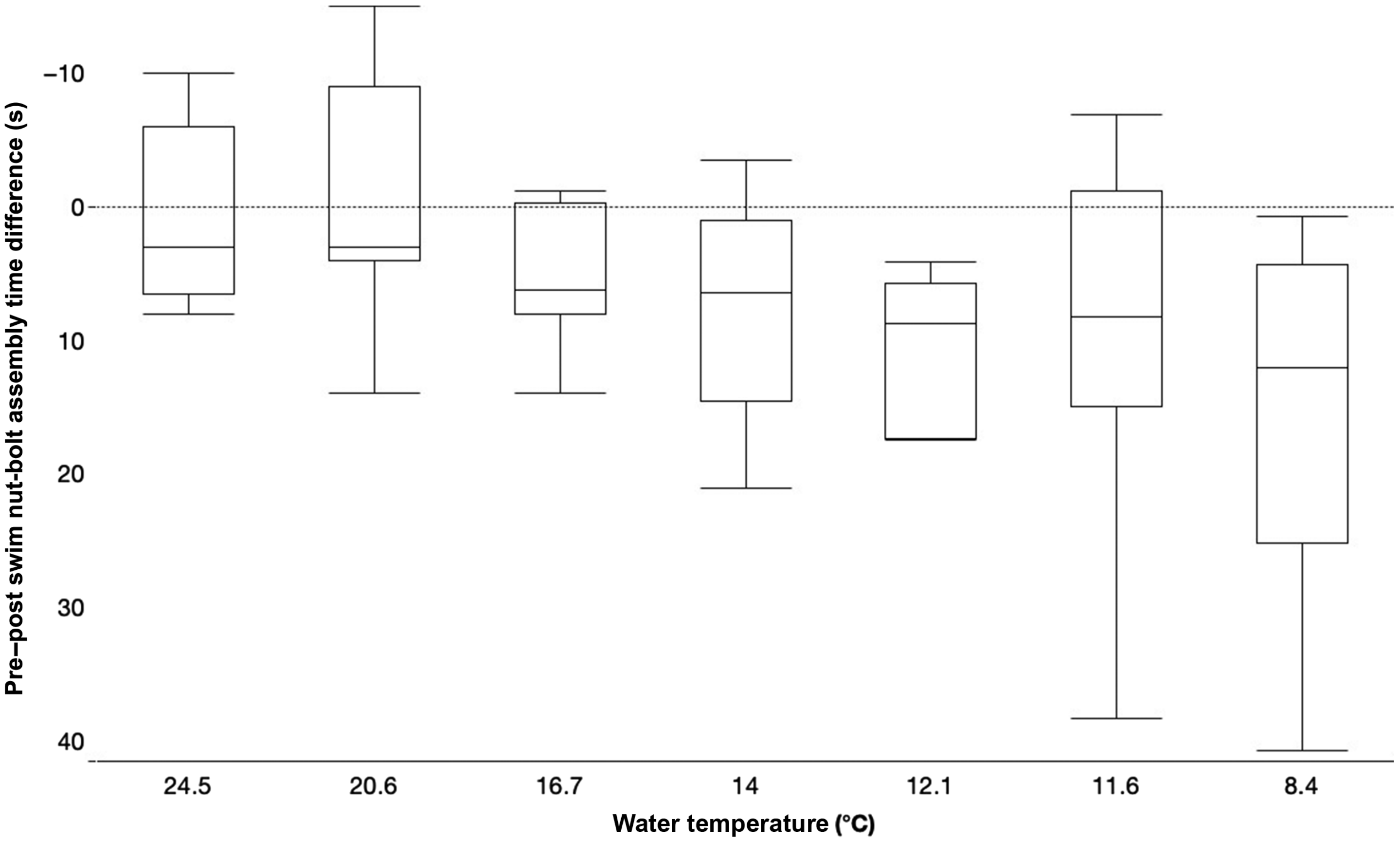

Figure 2 — Water temperature versus pre–post difference in nut–bolt assembly time for 9 swimmers. Median (horizontal line), interquartile range (box), and upper and lower recorded values (whiskers). The axes are reversed for ease of interpretation so that increased dexterity is visualized by an increase in the *y*-axis and increasing cold increases with the *x*-axis. Thus, decreased time to assemble the nut–bolt indicates better dexterity.

core temperature, cognitive function as measured by preswim minus postswim Stroop test results was associated with both decreasing water temperature (1.07 points score reduction; SE 0.204) per 1 °C decline in water temperature ($R^2 = .524$; $P < .0001$; Figure 4) and decreasing core temperature (estimate – 38.9 points score reduction; SE 7.529) per 1 °C decline in core temperature ($R^2 = .035$, $P = .0067$). Skin temperature decreased with water temperature (left forearm $R^2 = .711$; $P < .0001$, right scapula

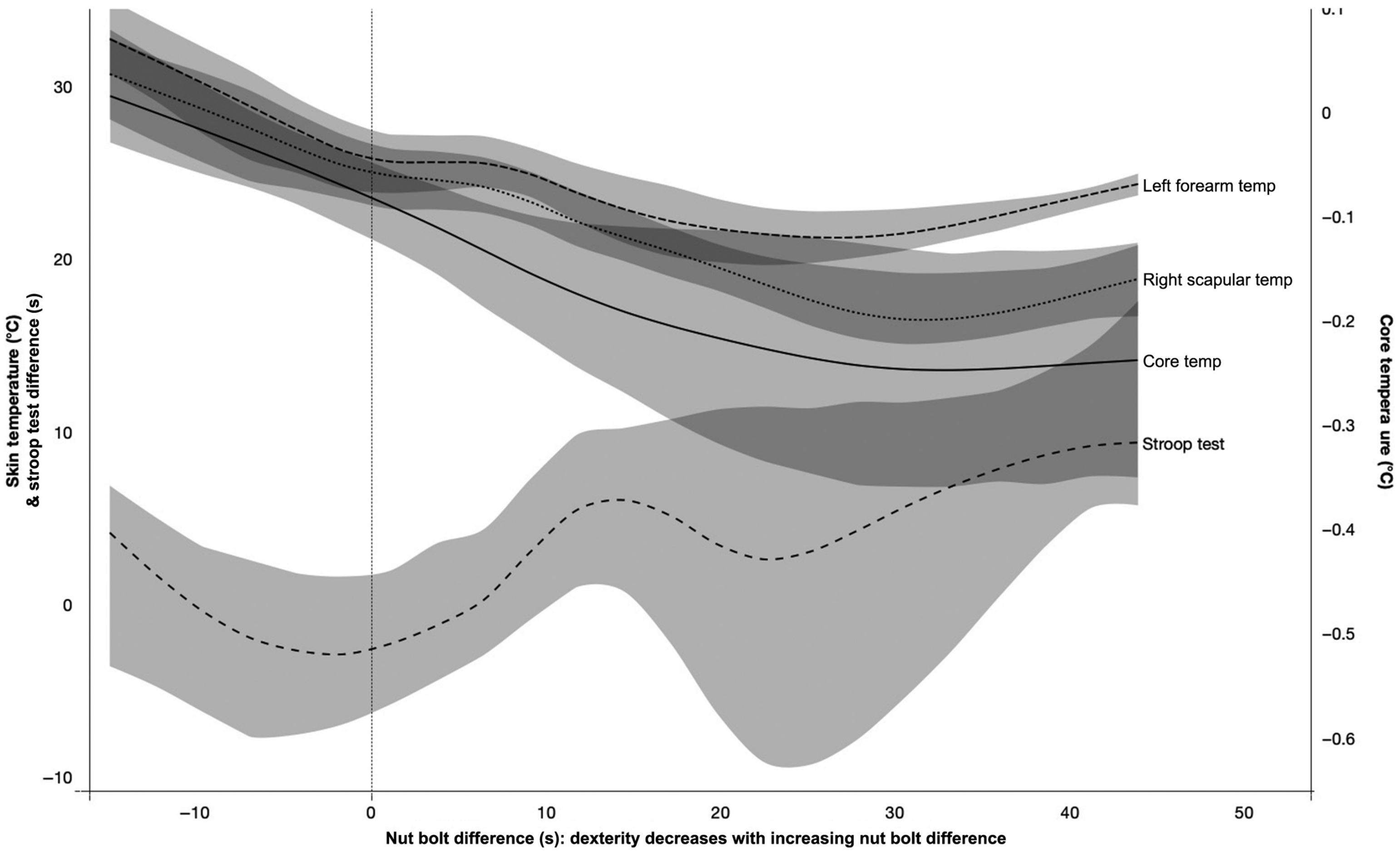

Figure 3 — Dexterity versus left forearm temperature minimum, right scapular temperature minimum, difference in preswim and postswim Stroop score (left *y*-axis), and decrease in core temperature (right *y*-axis) for 9 swimmers. Means and 95% CIs. Increasing pre–post swim nut–bolt assembly time difference equates with decreasing dexterity.

Table 4 Core and Skin Temperatures Versus Water Temperature in Wetsuited Freshwater Swimmers, Mean (95% CI)

Water temperature, °C	Core temperature		Right scapular temperature		Left forearm temperature	
	Minimum, °C	Decrease, °C	Minimum, °C	Decrease, °C	Minimum, °C	Decrease, °C
24.5	37.6 (37.4 to 37.9)	–0.07 (–0.15 to 0.01)	31.3 (30.8 to 31.9)	–1.7 (–3.6 to 0.1)	31.8 (30.3 to 33.2)	–2.7 (–4.1 to –1.3)
20.6	37.9 (37.6 to 38.2)	–0.05 (–0.16 to 0.07)	28.6 (27.2 to 30)	–2.8 (–4.3 to –1.4)	29.7 (27.7 to 31.7)	–4.3 (–6 to –2.6)
16.7	37.5 (37.3 to 37.8)	–0.11 (–0.22 to –0.00)	25.1 (23.7 to 26.5)	–5.2 (–6.7 to –3.6)	25.6 (23.7 to 27.6)	–4.2 (–7 to –1.3)
14	37.6 (37.4 to 37.7)	–0.14 (–0.28 to 0.00)	22.2 (20.7 to 23.6)	–7.7 (–9.4 to –5.9)	24.4 (22.3 to 26.6)	–6.2 (–8.1 to –4.3)
12.1	37.7 (37.5 to 37.9)	–0.13 (–0.27 to 0.00)	20.2 (19.4 to 20.9)	–10.2 (–11.8 to –8.6)	22.5 (21 to 24)	–7.9 (–9.5 to –6.3)
11.6	37.6 (37.4 to 37.9)	–0.21 (–0.43 to 0.00)	20.4 (18.1 to 22.6)	–10.4 (–13.3 to –7.4)	22.6 (20.1 to 25.2)	–9 (–11.7 to –6.2)
8.4	37.5 (37.3 to 37.8)	–0.14 (–0.27 to –0.01)	17.6 (15.9 to 19.2)	–13.3 (–15.3 to –11.2)	19.9 (17.4 to 22.4)	–10.6 (–13.5 to 7.7)
R^2	.008	.041	.877	.722	.711	.446
Estimated change (°C) per 1 °C change in water temperature	0.005	0.007	0.884	0.746	0.747	0.486
P	.5113	.14	**<.0001**	**<.0001**	**<.0001**	**<.0001**

Note: Data from 9 swimmers doing self-paced self-limited swims in fresh open water (see Table 2). Statistically significant differences by bivariate fit are marked with bold font.

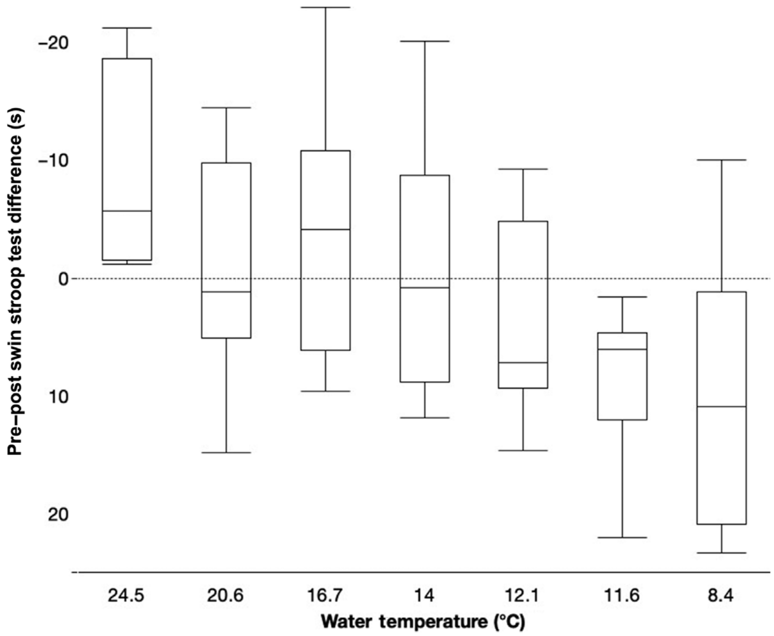

Figure 4 — Water temperature versus pre–post swim difference in Stroop test score for 9 swimmers. Median (horizontal line), interquartile range (box), and upper and lower recorded values (whiskers). The axes are reversed for ease of interpretation so that decreased cognitive performance is visualized by a decrease in the *y*-axis and increasing cold increases with the *x*-axis.

$R^2 = .877$; $P < .0001$). The left forearm was consistently warmer than the right scapula (Table 4).

Table 5 lists the statistical associations between variables and outcomes as calculated by a mixed-model linear regression analysis with the swimmer as a random factor. Correlated variables (1. BMI, total body fat percentage, and fat mass; 2. minimum temperature and maximum decrease in core temperature, left forearm, and right scapular temperatures; and 3. swim speed, swim duration, and

Table 5 Repeated-Measures Analysis of Variables and Outcomes

	Variable							
			Core temperature					
Outcome	**Water temperature, °C**	**Air temperature, °C**	**Preswim, °C**	**Decrease, °C**	**Swim speed, m/s**	**Body mass index, kg/m^2**	**Total body fat, %**	**Age**
Left forearm temperature minimum								
P	**<.0001**			.1509	.9973		.3386	
Estimate	**0.7047**			1.4441	−0.0051		−0.1304	
SE	**0.024**			0.9867	1.4967		0.127	
Right scapula temperature minimum								
P	**<.0001**			.1989	.3944		.1839	
Estimate	**0.87922**			1.6597	−1.6597		−0.1094	
SE	**0.03132**			1.2726	1.9272		0.0751	
Core temperature preswim								
P		.900				**.0064**		.2177
Estimate		0.0005				**−0.050**		−0.0080
SE		0.004				**0.012**		0.0059
Core temperature minimum								
P	.1080		**<.0001**		.9318	.3759		
Estimate	0.0058		**0.7352**		−0.0186	−0.0092		
SE	0.0035		**0.0917**		0.2157	0.0099		
Core temperature decrease								
P	.1080		**.0059**		.9318	.3759		
Estimate	0.0058		**−0.2648**		−0.0186	−0.0092		
SE	0.0035		**0.0917**		0.2157	0.0099		
Stroop test difference								
P	**.0002**			**.0067**	.3407		.0598	
Estimate	**−0.973**			**−22.34**	10.395		−0.340	
SE	**0.237**			**7.456**	10.581		0.158	

Note: Data from 9 swimmers doing repeated self-paced self-limited swims in fresh open water (see Table 2). Statistically significant effects from linear mixed model regression analyses are marked with bold font.

swim distance) were grouped and individually included in the model to find the model with the lowest Akaike Information Criterion.[39] In Table 5, if a variable is listed as a significant predictor of outcome, it indicates that it is the better model compared with its correlated variables. Findings of interest included the following:

1. Preswim core temperature affected the core temperature minimum and negatively affected the core temperature maximum decrease.
2. Decreasing core temperature decreased cognitive performance as measured by preswim minus postswim Stroop test difference.
3. BMI affected the preswim core temperature.
4. Water temperature did not affect swim speed (correlation .157 [−.106 to .399] $P = .24$).

There was no significant association between glove use and dexterity ($P = .117$) or between neoprene hat use and Stroop score ($P = .310$). The subjective swimmer reports found that wetsuits were well fitting, except for swimmer 2 who was aware of water inflow at the back of their neck. Nearly all swimmers reported feeling cold in the water or on exiting it with water temperature 14.0 °C, although all swimmers reported that the subsequent swim at 12.1 °C felt relatively good. At 11.6 °C water temperature, swimmers began to record symptoms of forehead pain or headache and cold extremities, with some noting decreased dexterity and “feel of the water.” By 8.4 °C, all swimmers reported the same, with some also experiencing dizziness and shivering. There were no episodes of hypothermia, syncope, or cause for intervention by the paramedic.

Discussion

The current study showed that manual dexterity, measured by the time required to successfully assemble 2 nut–washer–bolt sets, was reduced following active wetsuited swimming in cold water. The increase in post–pre swim nut–bolt assembly time was statistically associated with decreasing water temperature, minimum left forearm temperature, minimum right scapular temperature, and increased time to complete the Stroop test. This is consistent with the anatomical pathway and cognitive processes involved in the control of fine hand movements. An increase of 14.6 seconds to complete the nut–bolt assembly from 24.5 °C to 8.4 °C water temperature, from a mean preswim time of 30.7 seconds (SD 8.1) represents a 47.5% increase. Although no swimmer failed to complete the nut–bolt assembly, this is a statistically and practically significant deterioration in performance that, although it did not affect swim speed, would have implications for the manipulation of equipment such as bicycles or transitions in triathlons.[24] Swimmers and event organizers should accordingly plan for compromised dexterity.

We detected a learning effect for the preswim nut bolt assembly test between the first (20.6 °C water temperature) and second (24.5 °C water temperature) swims but not with any subsequent swims. Any learning effect would act to decrease the nut–bolt assembly times, whereas the effects of cold water would increase the time required to complete the test. Thus, we would expect a learning effect to diminish the decrease in dexterity associated with cold water found in this study. We may consequently have underreported the deterioration in dexterity associated with cold-water wetsuited swimming.

Core temperature minimum was not found to be associated with any outcomes. However, the decrease in core temperature (preswim core temperature − core temperature minimum) was associated with Stroop score, right scapular, and left forearm temperatures. This suggests that a relative rather than absolute decrease in temperature within the range reported in this paper has an impact on dexterity and cognitive function. The decrease in Stroop score was correlated with decreasing water temperature but not absolute core temperature. This may be interpreted as evidence for the distracting effects of cold water on attention, executive function, speed of processing, and memory.[5]

Body habitus as determined by DXA scan did not impact peripheral or core body temperature; this may be due to the insulating properties and boundary layer provided by the wetsuits. Interestingly, although both left forearm and right shoulder skin temperatures decreased with water temperature, the forearm remained warmer than the scapula. This could reflect increased heat production in the forearm while swimming or less water ingress and subsequent cooling compared with the back of the wetsuit where the mechanics of shoulder rotation facilitate water entry. As uninsulated skin approaches the ambient water temperature in both resting and exercising states, the insulating effects of wetsuits may decrease the temperature gradient between the deep tissues and skin and therefore increase dexterity as a result of relatively preserved muscle temperature and function compared with the “naked” state.[40] That preswim core temperature was positively correlated with core temperature minimum and negatively correlated with core temperature decrease may be interpreted as either the potentially protective nature of anticipatory thermogenesis[41] or that a warm body is better able to compensate for cold exposure.

The primary strength of this study is that it was conducted in the field rather than the laboratory, making its findings applicable to open water swimmers and triathletes. That the study was conducted with trained and highly trained club swimmers similarly allows its application to a much larger population than if only elite swimmers were studied.[32] The use of DXA scans allowed for a more nuanced analysis of the swimmers’ body composition than is possible with BMI or skinfold thickness.[42] The crossover cohort design of the study increased its statistical power and was representative of the training and acclimatization of open water swimmers with progressively colder water as the season progressed. Circadian temperature fluctuations[43] should have been minimized because all swims started at approximately the same time, except the last, which started approximately 2 hours earlier due to decreased daylight. The pragmatic nature of the study in which some swimmers supplemented their insulation with neoprene hats and gloves with colder water temperature increases the study’s applicability to real-world cold water swims. The range of study water temperatures (8.4 °C–24.5 °C) corresponds well to temperate sea surface temperatures for much of the year[44] and therefore may be used in the planning and risk assessment of open water swims.

That hand skin temperature is a major determinant of dexterity in cold water immersion is well established.[7–9,45] The pragmatic difficulty of not being able to measure hand and finger temperature during the swim was a major limitation, and in consequence, we were unable to account for cold induced vasodilation,[46] which may affect dexterity.

The small number of participants, although providing sufficient power for the primary outcome, did not allow for subanalyses by sex, age, or body habitus, which may have allowed a more nuanced analysis of correlations. Several validated dexterity tests exist.[47] However, our group had previously conducted cold-water dexterity research in special forces soldiers,[33] who valued a test in which practical parallels with their operational tasks could be drawn. We continued with the technique familiar to us. The learning effect found between the first 2 swims may indicate that the participants were not given sufficient opportunity to practice for the tests prior to study commencement. Cooling of the lower motor neurons, especially the ulna nerve,[4] may be of particular importance in cold water swimming. However, it is difficult to extrapolate muscle and nerve temperature from skin temperature, particularly if interindividual and intraindividual differences in limb size and insulation are considered.[48] The practicalities of invasive muscle temperature measurement with a wetsuit and concerns over the possibility of infection in a freshwater lake prohibited such measurement. The DXA scan, although considered the reference standard for measuring body composition, was only measured prior to the first swim. Consequently, we would not have detected any changes in body composition during the duration of the study, which, given that BMI was correlated with preswim core temperature, might be of interest.[49]

The study was conducted in open water and seasonal progression meant that it was not possible to randomize the water temperatures of the swims. To minimize the effect of climatic conditions on the preswim and postswim testing, a tent was provided, although this was at ambient temperature. Participants' swim training in the study period was not standardized and may also have influenced the findings. This lack of randomization and standardization could potentially have resulted in acclimatization to colder water as the swim season progressed, negatively biasing our findings. If so, true effects of cold open water may be more pronounced than reported in this study.

Practical Applications

Laboratory studies have found decreased dexterity with both local and systemic cooling in passive subjects and decreased grip strength and bicycle technique after cold flume swims.[24] This paper demonstrates decreased dexterity in active, open water wetsuited swimmers, validating previous studies and demonstrating their applicability in the field. That dexterity decreases with water temperature has implications for both swim efficiency and safety. Much emphasis has been placed on hypothermia as a safety concern,[50] but open water swimmers, triathletes, and event organizers should consider the implications of reduced dexterity for safety, performance, and equipment utilization both during the swim and during subsequent activity.[24]

The core temperature minimum and core temperature decrease were correlated to the preswim core temperature (Table 5). This suggests that measures to maintain swimmers' core temperature up to the moment of insertion may lessen subsequent temperature decrease.[50]

Future research should incorporate continuous or discrete measurements of finger and hand temperature to determine if increased blood flow associated with swimming moderates cold-induced vasodilation and dexterity and if whole-body cold exposure rather than isolated hand exposure potentiates or ameliorates these effects.

Conclusions

This crossover cohort study of open-water swimmers found that manual dexterity decreased with decreasing water temperature in the range 8.4 to 24.5 °C, despite the use of wetsuits. The decrease in dexterity was correlated with a decreased forearm and scapular skin temperature and decreased cognitive function. Core body temperature did not affect dexterity, although a relative decrease in core temperature was associated with decreased cognitive function. Water temperature did not affect swim speed; similarly, body composition as assessed by DXA scan had minimal effect on dexterity, cognition, or peripheral and core body temperatures. Open-water swimmers, triathletes, and event organizers should consider the implications of reduced dexterity for safety, performance, and equipment utilization.

Acknowledgments

We would like to thank Dag Rinden and Bjørnar Schau for their help with data acquisition. **Funding**: The study was funded by Akershus University Hospital, ABB Sponsorfond, Hans Rasmus Astrup (deceased), Olav Thon Stiftelsen, Romerike Sparebank, Stiftelsen, Trøgstad Brannkasse, Tømmerruta, and Viken Fylkeskommune.

References

1. Golden F, Tipton M. *Essentials of Sea Survival*. Human Kinetics; 2002.
2. van Houwelingen J, Schreven S, Smeets JB, Clercx HJ, Beek PJ. Effective propulsion in swimming: grasping the hydrodynamics of hand and arm movements. *J Appl Biomech*. 2017;33(1):87–100. doi:10.1123/jab.2016-0064
3. Sobinov AR, Bensmaia SJ. The neural mechanisms of manual dexterity. *Nat Rev Neurosci*. 2021;22(12):741–757. doi:10.1038/s41583-021-00528-7
4. Tipton M, Bradford C. Moving in extreme environments: open water swimming in cold and warm water. *Extrem Physiol Med*. 2014;3:12. doi:10.1186/2046-7648-3-12
5. Falla M, Micarelli A, Hüfner K, Strapazzon G. The effect of cold exposure on cognitive performance in healthy adults: a systematic review. *Int J Environ Res Public Health*. 2021;18(18):9725. doi:10.3390/ijerph18189725
6. Payne S, Macintosh A, Stock J. The influence of digit size and proportions on dexterity during cold exposure. *Am J Phys Anthropol*. 2018;166(4):875–883. doi:10.1002/ajpa.23486
7. Gaydos HF, Dusek ER. Effects of localized hand cooling versus total body cooling on manual performance. *J Appl Physiol*. 1958;12(3):377–380. doi:10.1152/jappl.1958.12.3.377
8. Chen W-L, Shih Y-C, Chi C-F. Hand and Finger Dexterity as a function of skin temperature, EMG, and ambient condition. *Hum Factors*. 2010;52:426–440. doi:10.1177/0018720810376514
9. Zander J, Morrison J. Effects of pressure, cold and gloves on hand skin temperature and manual performance of divers. *Eur J Appl Physiol*. 2008;104(2):237–244. doi:10.1007/s00421-008-0715-9
10. Maley MJ, Minett GM, Bach AJE, Zietek SA, Stewart KL, Stewart IB. Internal and external cooling methods and their effect on body temperature, thermal perception and dexterity. *PLoS One*. 2018;13(1):e0191416. doi:10.1371/journal.pone.0191416
11. Heus R, Daanen HAM, Havenith G. Physiological criteria for functioning of hands in the cold: a review. *Appl Ergon*. 1995;26(1):5–13. doi:10.1016/0003-6870(94)00004-I
12. Ofir D, Yanir Y, Eynan M, Arieli Y. Evaluating the thermal protection provided by a 2–3 mm wet suit during fin diving in shallow water with a temperature of 16–20°C. *Diving Hyperb Med*. 2019;49(4):266–275. doi:10.28920/dhm49.4.266-275
13. Cheung SS, Montie DL, White MD, Behm D. Changes in manual dexterity following short-term hand and forearm immersion in 10 degrees C water. *Aviat Space Environ Med*. 2003;74(9):990–993.

14. De Jesus PV, Hausmanowa-Petrusewicz I, Barchi RL. The effect of cold on nerve conduction of human slow and fast nerve fibers. *Neurology*. 1973;23(11):1182–1189. doi:10.1212/wnl.23.11.1182
15. Herrera E, Sandoval MC, Camargo DM, Salvini TF. Motor and sensory nerve conduction are affected differently by ice pack, ice massage, and cold water immersion. *Phys Ther*. 2010;90(4):581–591. doi:10.2522/ptj.20090131
16. Wakabayashi H, Wijayanto T, Tochihara Y. Neuromuscular function during knee extension exercise after cold water immersion. *J Physiol Anthropol*. 2017;36(1):28. doi:10.1186/s40101-017-0144-8
17. Mallette MM, Green LA, Gabriel DA, Cheung SS. The effects of local forearm muscle cooling on motor unit properties. *Eur J Appl Physiol*. 2018;118(2):401–410. doi:10.1007/s00421-017-3782-y
18. Oksa J, Rintamäki H, Mäkinen T, Hassi J, Rusko H. Cooling-induced changes in muscular performance and EMG activity of agonist and antagonist muscles. *Aviat Space Environ Med*. 1995;66(1):26–31.
19. Sekihara C, Izumizaki M, Yasuda T, Nakajima T, Atsumi T, Homma I. Effect of cooling on thixotropic position-sense error in human biceps muscle. *Muscle Nerve*. 2007;35(6):781–787. doi:10.1002/mus.20779
20. Oksa J, Rintamäki H, Mäkinen T. The effect of training of military skills on performance in cold environment. *Mil Med*. 2006;171(8):757–761. doi:10.7205/milmed.171.8.757
21. Shoemaker LN, Wilson LC, Lucas SJE, Machado L, Thomas KN, Cotter JD. Swimming-related effects on cerebrovascular and cognitive function. *Physiol Rep*. 2019;7(20):e14247. doi:10.14814/phy2.14247
22. Donnan K, Williams EL, Morris JL, Stanger N. The effects of exercise at different temperatures on cognitive function: a systematic review. *Psychol Sport Exerc*. 2021;54:101908. doi:10.1016/j.psychsport.2021.101908
23. Palinkas LA. Mental and cognitive performance in the cold. *Int J Circumpolar Health*. 2001;60(3):430–439. doi:10.1080/22423982.2001.12113048
24. Saycell J, Lomax M, Massey H, Tipton M. Scientific rationale for changing lower water temperature limits for triathlon racing to 12°C with wetsuits and 16°C without wetsuits. *Br J Sports Med*. 2018;52(11):702–708. doi:10.1136/bjsports-2017-098914
25. Knechtle B, Christinger N, Kohler G, Knechtle P, Rosemann T. Swimming in ice cold water. *Ir J Med Sci*. 2009;178(4):507–511. doi:10.1007/s11845-009-0427-0
26. Waag T, Hesselberg O, Reinertsen RE. Heat production during cold water immersion: the role of shivering and exercise in the development of hypothermia. *Arctic Med Res*. 1995;54(suppl 2):60–64.
27. Fact.MR. Wetsuit market. 2024. Accessed January 8, 2024. https://www.factmr.com/report/856/wetsuit-market
28. World Aquatics. *Competition Regulations*. World Aquatics; 2024.
29. World Triathlon. *2024 Competition Rules*. World Triathlon; 2024.
30. Xu X, Giesbrecht GG. A new look at survival times during cold water immersion. *J Therm Biol*. 2018;78:100–105. doi:10.1016/j.jtherbio.2018.08.022
31. Lafère P, Guerrero F, Germonpré P, Balestra C. Comparison of insulation provided by dry or wetsuits among recreational divers during cold water immersion (<5°C). *Int Marit Health*. 2021;72(3):217–222. doi:10.5603/imh.2021.0040
32. McKay AKA, Stellingwerff T, Smith ES, et al. Defining training and performance caliber: a participant classification framework. *Int J Sports Physiol Perform*. 2022;17(2):317–331. doi:10.1123/ijspp.2021-0451
33. Melau J, Hisdal J, Solberg PA. Impact of a 10,000-m cold-water swim on Norwegian naval special forces recruits. *J Spec Oper Med*. 2021;21(3):55–59. doi:10.55460/qe23-511p
34. Gosselin J, Béliveau J, Hamel M, et al. Wireless measurement of rectal temperature during exercise: Comparing an ingestible thermometric telemetric pill used as a suppository against a conventional rectal probe. *J Therm Biol*. 2019;83:112–118. doi:10.1016/j.jtherbio.2019.05.010
35. Stroop JR. Studies of interference in serial verbal reactions. *J Exp Psychol*. 1935;18(6):643–662.
36. Allampati S, Wen S, Liu F, Kupec JT. Recovery of cognitive function after sedation with propofol for outpatient gastrointestinal endoscopy. *Saudi J Gastroenterol*. 2019;25(3):188–193. doi:10.4103/sjg.SJG_369_18
37. Bajaj JS, Heuman DM, Sterling RK, et al. Validation of EncephalApp, smartphone-based stroop test, for the diagnosis of covert hepatic encephalopathy. *Clin Gastroenterol Hepatol*. 2015;13(10):1828–1835.e1. doi:10.1016/j.cgh.2014.05.011
38. Bursac Z, Gauss CH, Williams DK, Hosmer DW. Purposeful selection of variables in logistic regression. *Source Code Biol Med*. 2008;3:17. doi:10.1186/1751-0473-3-17
39. Dziak JJ, Coffman DL, Lanza ST, Li R, Jermiin LS. Sensitivity and specificity of information criteria. *Brief Bioinform*. 2020;21(2):553–565. doi:10.1093/bib/bbz016
40. Lee DT, Toner M, McArdle W, Vrabas I, Pandolf K. Thermal and metabolic responses to cold-water immersion at knee, hip, and shoulder levels. *J Appl Physiol*. 1997;82:1523–30. doi:10.1152/jappl.1997.82.5.1523
41. Stjepanovic M, Nikolaidis PT, Knechtle B. Swimming three ice miles within fifteen hours. *Chin J Physiol*. 2017;60(4):197–206. doi:10.4077/cjp.2017.Baf467
42. Henriksen HB, Alavi DH, Blomhoff R. Precision of Lunar Dual-energy X-ray Absorptiometry (iDXA) in measuring body composition among colorectal cancer patients and healthy subjects. *Clin Nutr ESPEN*. 2021;44:316–323. doi:10.1016/j.clnesp.2021.05.025
43. Refinetti R. Circadian rhythmicity of body temperature and metabolism. *Temperature*. 2020;7(4):321–362. doi:10.1080/23328940.2020.1743605
44. The Intergovernmental Panel on Climate Change. Ocean, cryosphere and sea level change. In: *Climate Change 2021—The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press; 2023:1211–1362.
45. Enander A. Performance and sensory aspects of work in cold environments: a review. *Ergonomics*. 1984;27(4):365–378. doi:10.1080/00140138408963501
46. Daanen HA. Finger cold-induced vasodilation: a review. *Eur J Appl Physiol*. 2003;89(5):411–26. doi:10.1007/s00421-003-0818-2
47. Causby R, Reed L, McDonnell M, Hillier S. Use of objective psychomotor tests in health professionals. *Percept Mot Skills*. 2014;118(3):765–804. doi:10.2466/25.27.PMS.118k27w2
48. Clarke RS, Hellon RF, Lind AR. The duration of sustained contractions of the human forearm at different muscle temperatures. *J Physiol*. 1958;143(3):454–473. doi:10.1113/jphysiol.1958.sp006071
49. Buckinx F, Landi F, Cesari M, et al. Pitfalls in the measurement of muscle mass: a need for a reference standard. *J Cachexia Sarcopenia Muscle*. 2018;9(2):269–278. doi:10.1002/jcsm.12268
50. Drigny J, Rolland M, Pla R, et al. Risk factors and predictors of hypothermia and dropouts during open-water swimming competitions. *Int J Sports Physiol Perform*. 2021;16(11):1692–1699. doi:10.1123/ijspp.2020-0875