The effects of exposure time, pressure and cold on hand skin temperature and manual performance when wearing three-fingered neoprene gloves

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Abstract

Cold water immersion and protective gloves are associated with decreased manual performance. Although neoprene gloves slow hand cooling, there is little information on whether they provide sufficient protection when diving in cold water. Nine divers wearing 3-fingered neoprene gloves and dry suits were immersed in water at 25 ^{o}C and at 4 ^{o}C, at depths of 0.5 msw and 40 msw in a hyperbaric chamber. Skin temperatures were measured at the hand, forearm, chest and head. Grip strength, tactile sensitivity and manual dexterity were measured at 3 time intervals. There was an exponential decay in finger and back of hand skin temperatures with exposure time in 4 ^{o}C water. Finger and back of hand skin temperatures were lower at 40 msw than at 0.5 msw. There was no effect of pressure or temperature on grip strength. Tactile sensitivity decreased linearly with finger skin temperature at both pressures. Manual dexterity was not affected by finger skin temperature at 0.5 msw, but decreased with fall in finger skin temperature at 40 msw. Results show that neoprene gloves do not provide adequate thermal protection in 4 ^{o}C water. Impairment of manual performance is dependent on the type of task, depth and exposure time.

Résumé

L’immersion dans l’eau froide et le port de gants de protection froids entraînent une diminution de la dextérité. Même si les gants de néoprène retardent le refroidissement des mains, il y a peu d’information permettant de savoir si ces gants assurent une protection suffisante lors d’une plongée en eau froide. Neuf plongeurs portant des gants de néoprène à 3 doigts et une combinaison étanche ont été immergés dans l’eau à 25 ºC et à 4 ºC, à des profondeurs simulées de 0,5 m et de 40 m en chambre hyperbare. La température de la peau a été mesurée aux mains, à l’avant-bras, à la poitrine et à la tête. La force de préhension, la sensibilité tactile et la dextérité ont été mesurées à 3 intervalles de temps donnés. Dans l’eau à 4 ºC, on a constaté une chute exponentielle de la température de la peau du dos de la main et des doigts en fonction de la durée d’exposition. À une profondeur de 40 m, la température de la peau des doigts et du dos de la main était inférieure à celle à 0,5 m de profondeur. La pression ou la température n’ont pas eu d’effet sur la force de préhension. La sensibilité tactile diminuait de façon linéaire par rapport à la température de la peau des doigts aux deux pressions. La température de la peau des doigts à une profondeur de 0,5 m n’a pas eu d’effet sur la dextérité, mais celle-ci a diminuée avec la chute de température de la peau des doigts à une profondeur de 40 m. Les résultats montrent que les gants de néoprène n’offrent pas une protection thermique suffisante dans l’eau à une température de 4 ^{o}C. La diminution de la dextérité dépend du type de tâche exécutée, de la profondeur et de la durée d’exposition.

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Executive summary

This study was designed to quantify the effects of exposure to cold water and increased pressure on the hand skin temperature and manual performance of divers wearing neoprene gloves. The majority of diving is completed in cold water, between approximately 8°C and 14°C, but temperatures as low as -2°C can be encountered in Canadian waters. To combat immersion in cold water, Canadian forces divers are equipped with full protective clothing, including 3-fingered Rubatex neoprene gloves. Exposure to cold and the use of protective gloves are both associated with decreased manual performance capabilities. Three-fingered neoprene gloves slow hand cooling and preserve hand function. However, there is little information on whether neoprene gloves provide sufficient insulation to maintain hand skin temperature when diving in cold water. Divers are particularly concerned with hand function because of the high manual performance requirement of underwater tasks. In the operational environment, divers require hand strength, fine motor control and tactile sensitivity. Although research that documents the detrimental effects of cold on manual performance is extensive, information on manual performance when diving in cold water and when wearing three fingered neoprene gloves is limited and largely anecdotal.

There were three objectives to this study: to determine change in the skin temperature over time; to quantify the effects of compression to 40 msw on the thermal protection provided by Rubatex neoprene gloves; and to identify the effect of hand skin temperature on manual performance capabilities of divers when wearing neoprene gloves.

Four experimental conditions were designed to identify the combined effects of cold, pressure and time on hand skin temperature and the related effect on manual performance when wearing three-fingered Rubatex neoprene gloves Nine divers wearing 3-fingered neoprene gloves and dry suits were immersed in water at 25 ^{o}C and at 4 ^{o}C, at simulated depths of 0.5 msw and 40 msw in a hyperbaric chamber. Skin temperatures were measured at the thumb, index finger, back of hand, forearm, chest and head. Grip strength, tactile sensitivity and manual dexterity were measure at three time intervals over a bottom time of approximately 27 min.

When wearing 3-fingered neoprene gloves in 4 oC water, divers' finger and hand skin temperatures decreased exponentially with time of exposure. Results indicate that when diving in 4 oC water, finger skin temperature will plateau at approx. 15 ^{o}C at 0.4 msw compared with 9 ^{o}C at 40 msw. Thus, at 40 msw, the neoprene gloves loose approximately 50% of their protective value due to the effect of pressure. Results also showed that the components of manual performance are affected differently by finger and hand cooling. When wearing neoprene gloves, grip strength is unaffected by pressure or time of exposure to cold water. Exposure to cold water results in progressively lower tactile sensitivity scores, with no significant difference between the two pressure conditions. The decrease in tactile sensitivity is approximately linear with finger skin temperature. Manual dexterity is unaffected by exposure time or skin temperature at 0.4 msw, however, manual dexterity decreases linearly as a function of skin temperature at 40 msw.

Of the three components of manual performance evaluated, tactile sensitivity appears to be the most sensitive to exposure to cold. The results also suggest that the effects of

gloves and skin temperature on manual dexterity are not necessarily additive, but are dependent on glove thickness. Although there is no loss of manual dexterity due to cooling at 0.4 msw, manual dexterity scores are lower at 0.4 msw compared to 40 msw due to the thicker neoprene material. Thus, although protective gloves will limit the drop in hand and finger skin temperatures, glove thickness will adversely affect manual performance and may outweigh the effect of cold. This means that when designing equipment for divers, ergonomic guidelines must consider the antagonism between the cumbersome effect of glove thickness and the degrading effect of cold. For example, results suggest that at 0.4 msw a thinner glove would improve manual dexterity at the expense of lower finger skin temperature and reduced tactile sensitivity. To properly evaluate diver performance it is essential that new glove designs are tested in realistic environmental conditions.

Sommaire

L’étude visait à quantifier les effets d’une exposition à l’eau froide et d’une augmentation de la pression sur la température de la peau des mains et sur la dextérité de plongeurs portant des gants de néoprène. La plupart des tâches de plongée se déroulent en eau froide, à des températures comprises entre 8 °C et 14 °C environ, mais les températures de certaines eaux canadiennes peuvent atteindre les -2 °C. Pour l’immersion en eau froide, les plongeurs de Forces canadiennes sont dotés de tenues de protection complètes, y compris des gants en néoprène à 3 doigts de type Rubatex. L’exposition au froid et le port de gants de protection froids entraînent une diminution de la dextérité. Les gants en néoprène à 3 doigts retardent le refroidissement des mains et permettent de conserver la fonction de la main. Il existe cependant peu d’information permettant de savoir si ces gants assurent une isolation suffisante pour maintenir une bonne température des mains lors d’une plongée en eau froide. Les plongeurs sont particulièrement préoccupés par la fonction de la main en raison de la grande dextérité qu’exigent les tâches sous l’eau. Dans l’environnement opérationnel, les plongeurs ont besoin de force de préhension, d’un contrôle moteur précis et de sensibilité tactile. Même si la recherche est exhaustive au sujet des effets défavorables du froid sur la dextérité, il y a très peu d’information sur la dextérité lors de plongées en eau froide et lorsque les plongeurs portent des gants de néoprène à 3 doigts. Et pour autant qu’il y en ait, cette information est généralement empirique.

L’étude visait trois objectifs : déterminer le changement de température de la peau avec le temps; quantifier les effets de la pression à une profondeur de 40 m sur la protection thermique qu’offrent les gants en néoprène Rubatex; déterminer l’effet de la température de la peau de la main sur la dextérité des plongeurs portant des gants de néoprène.

Quatre conditions expérimentales ont été établies pour déterminer les effets combinés du froid, de la pression et de la durée d’exposition sur la température de la peau des mains et sur l’effet connexe sur la dextérité lorsque le plongeur porte des gants en néoprène à 3 doigts Rubatex. Neuf plongeurs portant des gants de néoprène à 3 doigts et une combinaison étanche ont été immergés dans l’eau à 25 ºC et à 4 ºC, à des profondeurs simulées de 0,5 m et de 40 m en chambre hyperbare. Les températures de la peau ont été mesurées au pouce, à l’index, au dos de la main, à l’avant-bras, à la poitrine et à la tête. La force de préhension, la sensibilité tactile et la dextérité ont été mesurées à trois intervalles donnés sur une période d’environ 27 minutes.

Lorsque les plongeurs portaient des gants de néoprène à 3 doigts dans l’eau à une température de 4 ºC, la température de la peau des mains et des doigts diminuait de façon exponentielle en fonction de la durée d’exposition. Les résultats montrent que, pendant la plongée dans l’eau à 4 ºC, la température de la peau des doigts atteignait un plateau d’environ 15 ºC, à une profondeur de 4 m par rapport à un plateau de 9 ºC, à une profondeur de 40 m. Ainsi, à une profondeur de 40 m, les gants de néoprène perdaient environ 50 % de leurs propriétés protectrices en raison de l’effet de la pression. Les résultats montrent aussi que le refroidissement des doigts et des mains influent différemment sur les composantes de la dextérité. Lorsque les plongeurs portent des gants de néoprène, la pression et la durée d’exposition à l’eau froide n’ont pas d’effet sur la force de préhension. L’exposition à l’eau froide diminue progressivement la sensibilité tactile, mais l’écart est négligeable entre les deux conditions de pression. La diminution

de la sensibilité tactile est à peu près linéaire par rapport à celle de la température de la peau des doigts. La durée d'exposition ou la température de la peau à une profondeur de 0,4 m n'ont pas d'effet sur la dextérité, mais cette dernière diminue d'une façon linéaire en fonction de la température de la peau à une profondeur de 40 m.

Des trois composantes de la dextérité évaluées, la sensibilité tactile semble être celle que l'exposition au froid touche le plus. Les résultats laissent à penser que les effets des gants et de la température de la peau sur la dextérité ne s'additionnent pas forcément, mais dépendent de l'épaisseur des gants. Même s'il n'y a pas de diminution de la dextérité en raison du refroidissement à une profondeur de 0,4 m, la dextérité est cependant moindre à une profondeur de 4 m qu'à une profondeur de 40 m en raison de l'épaisseur du tissu de néoprène. Par conséquent, même si les gants de protection limitent la chute de la température de la peau des mains et des doigts, l'épaisseur des gants a un effet défavorable sur la dextérité et peut surpasser l'effet du froid. Cela signifie qu'au moment de concevoir de l'équipement de plongée, les directives en matière d'ergonomie doivent tenir compte des aspects contraires de l'encombrement de gants épais par rapport à l'effet défavorable du froid. Par exemple, les résultats donnent à penser que des gants minces à une profondeur de 0,4 m pourraient améliorer la dextérité au dépend d'une température plus basse de la peau des doigts et d'une diminution de la sensibilité tactile. Pour bien évaluer le rendement des plongeurs, il est essentiel que les nouveaux modèles de gants fassent l'objet d'essais dans des conditions environnementales réalistes.

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Introduction

The majority of diving is completed in cold water, between approximately 8 °C and 14 °C (Bowen, 1968; Egstrom, 1997), but temperatures as low as –2 °C can be encountered in Canadian waters. To combat immersion in cold water, Canadian forces divers are equipped with full protective clothing, including 3-fingered Rubatex® G-231-N neoprene gloves. Exposure to cold and the use of protective gloves are associated with decreased manual performance capabilities (Parsons and Egerton, 1985; Parsons, 2003). Three-fingered neoprene gloves slow hand cooling and preserve hand function; however, there is little information on whether neoprene gloves provide sufficient insulation to maintain hand skin temperature when diving in cold water. Divers report that in some operational environments the gloves are so cumbersome that they remove them in order to complete tasks that require either good tactile sensitivity or fine motor control (Morrison *et al.,* 1997). Removing the gloves accelerates hand cooling, and may lead to further decreases in manual performance capabilities.

Divers are particularly concerned with hand function because of the high manual performance requirement of underwater tasks. In the operational environment, divers require hand strength, fine motor control and tactile sensitivity. When compared to exposure to other environmental stressors, such as heat, increased pressure or wind, exposure to cold is reported to be the environmental factor that most significantly affects manual performance (Mackworth, 1953; Bowen, 1968; Stang and Wiener, 1970; Geisbrecht and Bristow,1992; Heus *et al.,* 1995,). The research that documents the detrimental affects of cold on manual performance is extensive (Horvath and Freeman, 1947; Mackworth, 1953; Mortens and Provins, 1960; Fox, 1967). However, information on manual performance when diving in cold water and when wearing three fingered neoprene gloves is limited and largely anecdotal.

Hand skin temperature is an important predictor of manual performance (Gaydos and Dusek, 1958; Enander, 1984; Schiefer *et al.,* 1984; and Geisbrecht *et al.,* 1995). Fox (1967) suggested that manual dexterity is degraded below a critical hand skin temperature of 8°C, and that tactile sensitivity is degraded below a critical temperature of 12° to 16° C. Further studies (Vincent and Tipton, 1988) have documented a decrease in finger dexterity starting below a skin temperature of 20-22° C, and becoming significant below 15- 16 ° C. Daanen (1993) documented decreased finger dexterity below 14° C. Part of the discrepancy is likely due to different experimental methods, both for simulating and measuring dexterity, and for measuring hand skin temperature.

Local cooling of the hand and arm decreases manual performance through both physical and neuromuscular pathways (Enander, 1998; Rissanen and Rintamaki , 2000). Local cooling decreases flexibility (LeBlanc *et al*., 1960; Geisbrecht and Bristow, 1992) due to increased viscosity in synovial fluid that interferes with smooth joint movements (Enander, 1998; Rissanen and Rintamaki, 2000). Decreased flexibility may also be caused by physical changes in the flexor and extensor muscles and tendons of the hand and fingers. As the soft tissue becomes cold, the fluid component becomes more viscous making movements more difficult (Enander 1998; Rissanen and Rintamaki, 2000; Geng, 2001). Cold also affects muscle activity through decreased ATP utilization, enzyme activity, calcium and acetylcholine release, and delayed cross bridge formation (Geisbrecht and Bristow, 1992). Cooling decreases the excitability of nerve membranes and nerve conduction velocity (LeBlanc, 1956; Bergh and Ekblom, 1979; Vincent and Tipton, 1988). This results in decreases in contraction velocity

(Bennett, 1984), maximal strength (Geisbrecht *et al*., 1995; Heus *et al*., 1995) and time to fatigue (Heus *et al.,* 1995).

This study is designed to quantify the effects of exposure to cold water and increased pressure on hand skin temperature and manual performance of divers wearing neoprene gloves. There are three objectives to this study: first to determine change in the skin temperature over time; second to quantify the effects of compression on the thermal protection provided by Rubatex ® G-231-N neoprene gloves; and third to identify the relationship between hand skin temperature and manual performance capabilities of divers wearing neoprene gloves. These data can be used in providing guidelines for the design of tools, equipment, and protective gloves to be used in cold water diving operations.

Methods

Subjects

Eleven male divers between 20 to 40 years, representative of the Canadian Forces divers, were recruited from the university population. Two participants did not complete the experiment. Participants were asked not to ingest alcohol, caffeine (coffee, tea, chocolate) or energy drinks, or to smoke cigarettes on the day of the experiment, and not to exercise in the four hours before the experiment and in the twelve hours after diving. The study was approved by the University Ethics Review Committee and Defence Research and Development Canada (Toronto).

Environmental Conditions

Four environmental conditions were selected to identify the effects of cold, pressure and exposure time on hand skin temperature and on manual performance of divers wearing three-fingered Rubatex ® G-231-N neoprene gloves. The experimental conditions are outlined in Table 1.

All conditions were completed in the wet section of a hyperbaric chamber at Simon Fraser University. For each condition divers were equipped with protective clothing including a dry suit, 3-fingered Rubatex ® neoprene gloves, and a neoprene hood. Subjects were seated at a table while immersed to the neck in water.

Table 1: Experimental Conditions

Condition	Water Temperature	Pressure	Gloves	Exposure time at start of test
1	25° C	0.4 msw	Yes	4 min.
2	25° C	40 msw	Yes	4 min.
3	4° C	0.4 msw	Yes	4, 11, and 18 min.
4	4° C	40 msw	Yes	4, 11, and 18 min.

Manual performance tests

Subjects completed a test battery of three manual performance tests in each condition: a measure of grip strength; a measure of tactile sensitivity; and a measure of manual dexterity. The tests are described in detail in (Morrison and Zander, 2005) and are summarised below.

Grip strength was measured using a hand grip dynamometer. Tactile sensitivity was measured using modified (enlarged) Braille characters. Subjects had to sense and identify the Braille characters by touch using a visual display of Braille characters as a reference source. Braille characters were presented on a board in 4 rows, with each row having progressively smaller character size and spacing. Tactile sensitivity score was measured as accuracy: the total number of characters correctly identified in 4 minutes (one minute per row). Manual dexterity was measured as the rate at which divers could pick up a series of 5/16 inch nuts and bolts supplied in two separate containers, assemble each nut and bolt and deposit in a third container. Manual dexterity score was measured as the total number of nut-bolt combinations correctly assembled in 2 minutes.

In each of the warm conditions (control) the diver completed the manual performance tests once. The test commenced four minutes after immersion of the hands in 25°C water. The effects of exposure to cold are considered to be time dependent. Therefore, in each of the cold conditions the divers completed three sequential test batteries starting at approximately four, eleven and eighteen minutes of exposure. The exposure time to 4° C water was selected to represent a typical bottom time for a Canadian forces mine-counter-measures dive. The scheduling of the tests provided adequate time for the diver to complete each test battery, and then remain with his hands immersed in the cold water for one to two minutes before starting the next set. Bottom times varied between 22 and 30 minutes depending on the progression of subjects through the test battery and their cold tolerance. One subject, who had the lowest hand skin temperatures, completed only two of the three test batteries in one condition.

The exposure to pressure required to achieve substantial compression of neoprene may also cause narcosis; thus, the two effects normally occur together. The effect of neoprene compression is not separated from the narcotic effect in this experiment. However, in a related study (Morrison and Zander, 2005), it was shown that narcosis did not have a significant effect on the manual performance tests used in this study.

Procedures

Divers were acclimatized to approximately 22 ° Celsius room temperature (in an air environment) for 30 minutes prior to dressing and entering the water. In conditions 2 and 4, divers were compressed to 40 msw at a compression rate of 18 $m.min^{-1}$. Divers were compressed whilst immersed to the neck in water and breathing air from the chamber environment. Manual performance tests commenced approximately 1.5 to 2.0 minutes after reaching bottom, and 4 minutes after immersing the hands in water. Each diver was accompanied by a dive tender. Divers were decompressed using the Canadian Forces Decompression Tables (Canadian Forces Air Diving Table 2- In-Water Oxygen Decompression). Each dive was followed by a one hour bends watch.

Thermocouples were used to measure skin temperature at eight sites: thumb, index finger, back of hand and forearm of the right arm, chest and head, and index finger and back of the left hand. The thermocouple junctions were attached to the skin using surgical tape and the wires were strung under the dry suit to emerge at the neck. Fine gauge thermocouples were used because they conformed to the movement of the diver’s body and fingers without becoming easily detached or affecting finger flexibility. The robust environmental conditions and test of maximum grip strength resulted in occasional damage to thermocouples and loss of data. Therefore, a total of five hand skin sites were used to allow for thermocouple damage and ensure a minimum of three valid hand skin temperature measures for each condition. Two measures of hand skin temperature are used in the analysis: finger temperature and back of hand temperature. Finger temperature is comprised of the mean of two finger sites: right thumb, and right index finger. Statistical analyses showed no significant difference between the three finger sites. Therefore, in the event of thermocouple damage, the left index finger is substituted to obtain a combination of two sites. Similarly, the back of hand temperature is either the right or left hand. The forearm position was chosen to identify differences in skin temperature of the underlying muscle between the smaller muscles of the hand and the larger muscles of the forearm. Chest and head temperature values were measured to confirm that skin temperatures of the head and torso remained within the normal range as an indication that there was no general cooling of the whole body.

A repeated measures design was used for all tests. To avoid a learning effect, divers were provided with training time both in the air and the water environment. Once test results plateaued to indicate an end to the learning curve, the divers progressed through the four conditions. To avoid an order effect due to practice or fatigue, divers progressed through the four environmental conditions in different orders.

Analysis

Data were analyzed in three ways: to determine hand skin temperatures as a function of exposure time when wearing neoprene gloves in cold water; to quantify change in manual performance with increasing exposure time to cold water; and to quantify manual performance abilities a function of finger and hand skin temperatures while wearing neoprene gloves. The mean and standard deviation of skin temperatures for 9 subjects was calculated at each skin measurement site at the start and end of the exposure to 4 ^{o}C water.

The mean finger and back of hand skin temperature data from conditions 3 and 4 were plotted to determine skin temperatures as a function of exposure time. Regression analyses were used to obtain best fit models for finger and back of hand skin temperatures when wearing neoprene gloves and exposed to 4 °C water.

Manual performance scores were compared using ANOVA to identify differences in manual performance associated with time of exposure to cold water, exposure to increased pressure, and any interaction between the two factors. Figure 1 shows the design of the statistical analysis.

	Time 0 25 degree Celsius	Time 1 4 degree Celsius 4 minutes	Time 2 4 degree Celsius 11 minutes	Time 3 4 degree Celsius 18 minutes
0.4 msw	Grip Strength Tactile Sensitivity Manual Dexterity	Grip Strength Tactile Sensitivity Manual Dexterity	Grip Strength Tactile Sensitivity Manual Dexterity	Grip Strength Tactile Sensitivity Manual Dexterity
40 msw	Grip Strength Tactile Sensitivity Manual Dexterity	Grip Strength Tactile Sensitivity Manual Dexterity	Grip Strength Tactile Sensitivity Manual Dexterity	Grip Strength Tactile Sensitivity Manual Dexterity

Figure 1: Experimental design

The third part of the analysis examined the relationship between manual performance and finger skin temperature. For each pressure condition (0.4 and 40 msw), the mean manual performance scores (tactile sensitivity and manual dexterity) were plotted against the mean skin temperatures (measured at the time at which each diver performed the particular task). Grip strength was not included in this analysis as there was no significant effect of cold or pressure on grip strength. The first data point represents the mean score of 9 subjects when immersed in 25 ^{o}C water. The remaining three data points represent the mean score at three sequential skin temperatures when immersed in 4^{o} C water. Linear regression analyses were used to determine the relationships between manual performance and finger skin temperature.

Results

Skin Temperatures

Mean and standard deviations of skin temperatures at the start and end of each exposure to 4 ^{o}C water are shown in Table 2. The data shows the mean skin temperature values of all 9 subjects, together with the depth condition and mean time of exposure. Results show that mean head and chest temperatures remained relatively stable with a fall of 0.2 to 2.6 ^{o}C over 25 to 27 minutes, while right forearm temperature fell by approximately 6 to 7 ^{o}C in both pressure conditions. The fall in forearm temperature was partly due to leakage of water at the wrist in some divers. By comparison, the mean back of hand temperature fell to 15.8 ^{o}C at 0.4 msw and to 12.4 ^{o}C at 40 msw. Mean finger temperature fell to approximately 13.6 ^{o}C at 0.4 msw and to 10.5 ^{o}C at 40 msw. At the end of the exposure, mean hand skin temperature of all five sites was colder at 40 msw than at 0.4 msw. The mean hand temperature measured over all five sites was 14.5 ^{o}C at 0.4w and 11.3 ^{o}C at 40 msw.

Table 2: Mean skin temperatures at start and end of exposure to 4 ^{o}C water (n=9)

Depth msw	Time min.	Right thumb	Right finger	Right hand	Right forearm	Chest	Head	Left finger	Left hand
0.4	0	25.7 ±4.3	26.6 ±4.0	23.4 ±7.3	29.9 ±4.2	34.2 ±1.1	34.1 ±0.7	26.1 ±3.0	25.2 ±5.5
0.4	25 ±4.2	13.9 ±3.5	13.4 ±3.5	15.6 ±5.7	23.5 ±7.7	31.9 ±2.1	33.9 ±1.0	13.9 ±4.3	15.9 ±4.9
40	0	29.7 ±4.2	30.2 ±1.7	28.6 ±7.3	32.3 ±2.5	34.0 ±1.1	34.4 ±0.7	28.9 ±4.4	26.8 ±7.2
40	26.9 ±2.7	10.5 ±1.8	10.3 ±1.6	12.7 ±1.9	26.3 ±6.9	31.7 ±1.9	31.8 ±2.1	10.7 ±1.9	12.1 ±4.5

Figure 2 shows the skin temperatures of one diver as a function of exposure time when immersed in 4^{o} C water at a pressure of 40 msw.

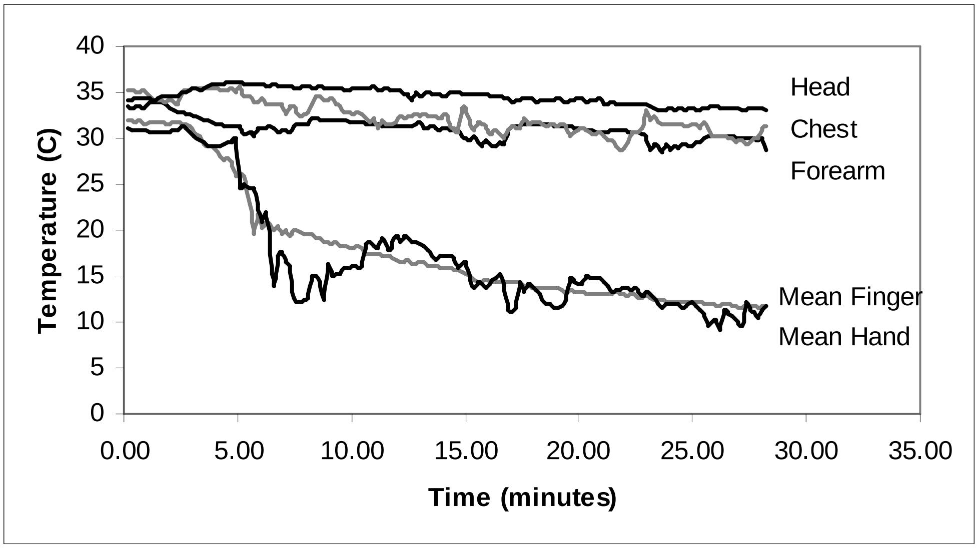

Figure 2: Skin temperatures (^{o}C) as a function of exposure time . Data of one diver: water temperature 4 ^{o}C; pressure 40 msw.

Figures 3 and 4 show the mean finger and back of hand temperatures as a function of exposure time when wearing 3-fingered gloves in cold water. Results are presented for a total exposure time of 27 minutes. As two subjects had exposure times of less than 25 minutes in one of the conditions, the data of only 7 of the subjects are included in figures 3 and 4. As the skin temperature data is non linear with time, an exponential function of the form $Tsk = A\ e^{-kt} + B$ was used to obtain a best fit to the data. In this model the sum of constants A and B represent the starting skin temperature (time = 0). B represents the skin temperature at which equilibrium is established and no further cooling takes place (the asymptote value of the exponential function). A represents the maximum drop in skin temperature. T = 1/k represents the rate of decay of skin temperature (the time constant of the exponential measured in minutes); thus, T represents the time at which 63% of the drop in skin temperature will have taken place. The best fit regression lines of the form

$Tsk = A\ e^{-kt} + B$ for the mean data of the seven subjects are shown in Figures 3 and 4 as broken lines.

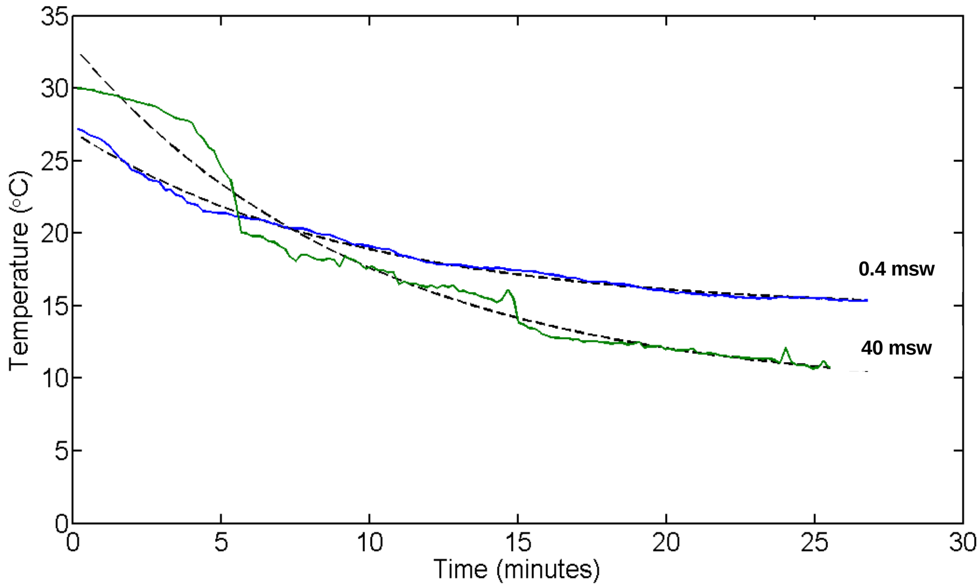

Figure 3: Finger skin temperature as a function of exposure time to 4° C water at 0.4 and 42 msw. Mean data of 7 subjects: blue = 0.4 msw; green = 40 msw; broken line = best fit regression

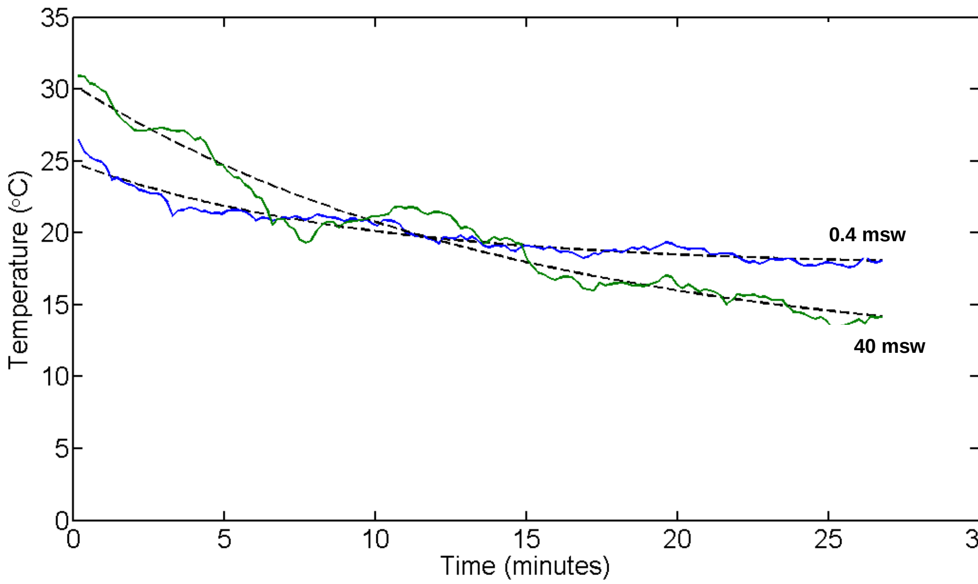

Figure 4: Back of hand temperature as a function of exposure time to 4° C water at 0.4 and 42 msw. Mean data of 7 subjects: blue = 0.4 msw; green = 40 msw; broken line = best fit regression.

Table 3 shows the parameters of the best-fit models of finger and back of hand skin temperatures as a function of exposure time to 4 ^{0}C water for the two pressure conditions.

Table 3: Best fit regression of finger and back of hand skin temperature (Tsk) as a function of cold exposure time (t) in minutes.

Finger Temperature ^{o}C	0.4 msw	Tsk=12.3*exp(-0.107*t)+14.7	r^2=0.99
	40 msw	Tsk = 24.0*exp(-0.102*t)+9.0	r^2=0.97
Back of Hand Temperature ^{o}C	0.4 msw	Tsk =7.2*exp(-0.108*t)+17.7	r^2=0.94
	40 msw	Tsk = 19.1*exp(-0.069*t)+11.2	r^2=0.95

The values of r^2 for the regression equations (Table 3) indicate that the models explain most of the variance in the data. The slightly lower correlation coefficients for back of hand temperature indicate that curves do not fit the data as well as for finger temperature. Possible reasons for the larger unexplained variance in back of hand temperature is water leaking into the gloves at the wrist due to hand movement and the smaller skin temperature change with time.

The regression equations of Table 3 indicate that finger skin temperature will reach equilibrium (steady state) at approximately 14.7 ^{o}C in 0.4 msw, compared with approximately 9 ^{o}C. in 40 msw. Thus at 40 msw, equilibrium temperature is reached at only 5 ^{o}C above water temperature, compared with a skin-water temperature difference of 10.7 ^{o}C at 0.4 msw. The best fit regressions for back of hand temperatures are similar to those of finger skin temperature except that the equilibrium temperature for back of hand is 2 – 3 ^{o}C warmer than for the finger. At 40 msw equilibrium temperature is reached at 7.2 ^{o}C above water temperature compared with 13.7 ^{o}C above water at 0.4 msw. These results indicate that at 40 msw the protective effect of neoprene gloves is reduced to approximately 50% of its surface value. The time constant of change in finger skin temperature is approximately 10 minutes at both 0.4 and 40 msw. The time constant for back of hand skin temperature is 10 min. at 0.4 msw and 16 min. at 40 msw.

Effect of exposure time and skin temperature on manual performance.

Grip strength

Results showed that there was no significant change in grip strength due to exposure to 4 ^{o}C water or increased pressure when wearing 3-fingered neoprene gloves.

Tactile Sensitivity

Scores are shown in Figure 5. There was an increased impairment of tactile sensitivity with time of exposure to 4^{o} C water at both pressures (F=12.0, p=0.00). The means and standard deviations at each time interval are given in Table 4 and statistical data are provided in Table 5.

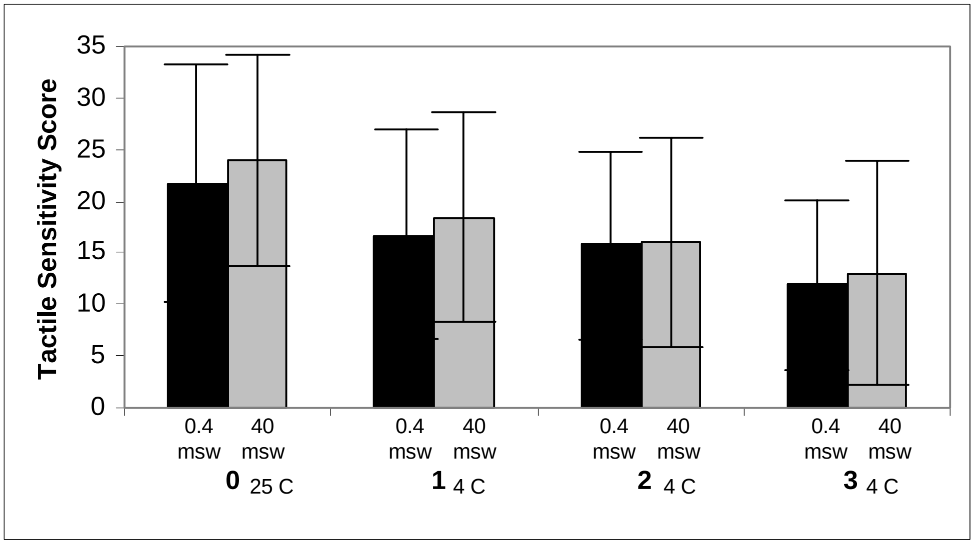

Figure 5: Tactile Sensitivity versus time of exposure.

Post-hoc analysis indicated that scores at time 3 (representing approximately 20 min. of exposure time) were significantly lower than scores at times 0, 1 and 2. Although there was no significant effect of pressure on tactile sensitivity there was a tendency for tactile sensitivity score to be higher at 40 msw (p = 0.08). There was no interaction effect between pressure and time of exposure. Statistical analysis indicates that exposure time accounts for 60% of the variance in the data ($\eta^2 = 0.6$).

Table 4: Effects of pressure and exposure time on tactile sensitivity

	Time 0 (25°C)	Time 1 (4°C)	Time 2 (4°C)	Time 3 (4°C)
Pressure 0.4 msw	21.6±11.8	16.6±10.3	15.8±9.2	12.0±8.1
Pressure 40 msw	24.0±10.1	18.4±10.3	16.1±10.2	13.0±11.1

Table 5: ANOVA of tactile sensitivity vs. pressure and time.

	F	Sig.	η^2	Power
Pressure	4.0	0.08	0.33	0.42
Time	12.0	0.00	0.60	1.00
Pressure x Time	0.2	0.92	0.02	0.51

Linear regression analysis was used to determine the relationship between mean tactile sensitivity scores and finger skin temperatures at 0.4 and 40 msw. Data for the warm condition (25 ^{0}C water) and the three sequential cold conditions (4 ^{0}C water) were used in the analysis. Results, shown in Figure 6, indicate that, when wearing neoprene gloves, tactile sensitivity is strongly correlated with finger skin temperature at both 0.4 msw ($r^2 = 0.92$) and 40 msw ($r^2 = 0.99$).

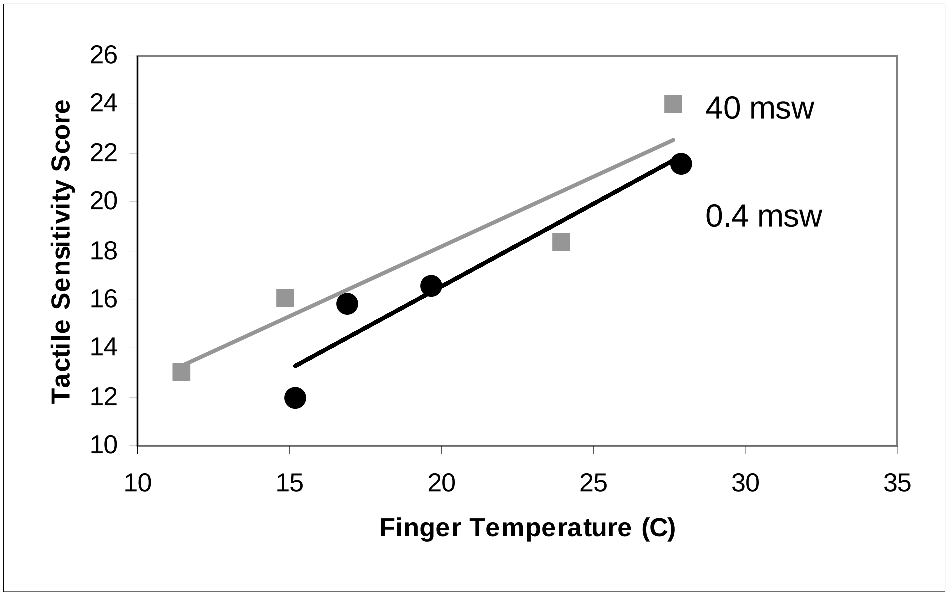

Figure 6: Relationship between tactile sensitivity score and mean finger temperature. Squares = mean data at 40 msw; circles = mean data at 0.4 msw

Manual Dexterity

The effects of pressure and time of exposure to cold water on manual dexterity are shown in Figure 7. The mean $\pm$ SD and statistical data are provided in Tables 6 and 7 respectively.

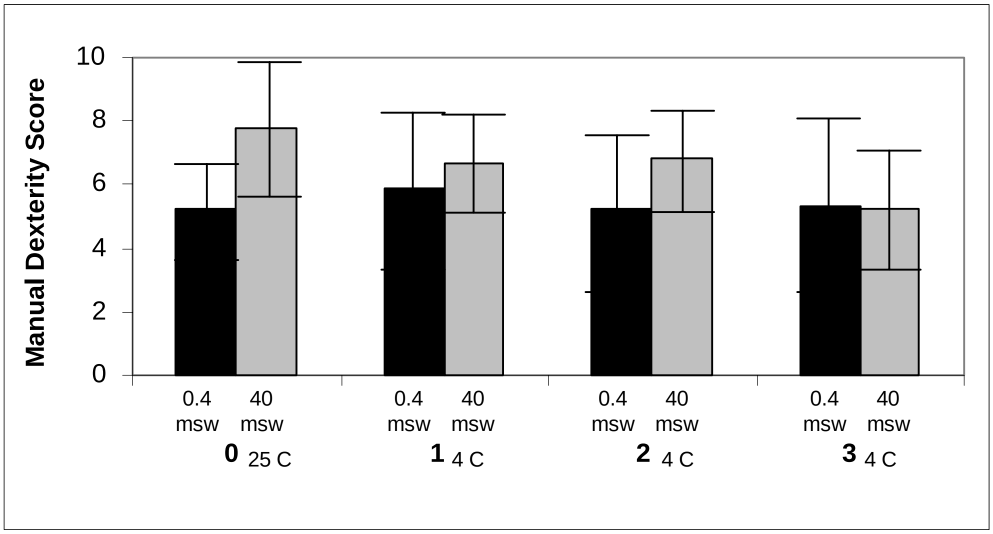

Figure 7: Manual Dexterity versus Time Condition

Statistical analysis revealed that there was a main effect of pressure on tactile sensitivity (p=0.006) and an interaction effect between pressure and time (p=0.006). Although there was no significant effect of exposure time on manual dexterity there was a trend towards a main effect (p=0.06). Figure 7 shows that at 40 msw there was an increasing impairment of manual dexterity with time of exposure to cold, whereas at 0.4 msw there was no change in manual dexterity with time. Post hoc analysis indicated a significant difference in manual dexterity due to pressure at time 0 (25 ^{o}C water), but no significant differences in the three cold conditions (times 1, 2, and 3). Thus, the improvement in manual dexterity achieved due to pressure at 40 msw is gradually lost with time due to the increasing effect of cold at 40 msw.

Table 6: Effects of pressure and exposure time on manual dexterity

	Time 0	Time 1	Time 2	Time 3
Pressure 0.4 msw	5.2±1.3	5.9±2.3	5.2±2.3	5.3±2.6
Pressure 40 msw	7.8±2.1	6.7±1.5	6.8±1.5	5.2±1.9

Table 7: ANOVA of manual performance vs. pressure and time

	F	Sig.	η^2	Power
Pressure	13.5	0.006	0.63	0.90
Time	2.8	0.06	0.26	0.60
Pressure x Time	0.53	0.006	0.40	0.88

The mean manual dexterity scores from all four temperature and pressure conditions (Table 1) were plotted against finger skin temperature. Regression analysis was used to determine the relationship between manual dexterity score and finger skin temperatures at 0.4 and 40 msw. Results shown in Figure 8 indicate that, when wearing neoprene gloves, there is no significant relationship between manual dexterity and finger skin temperature at 0.4 msw ($r^2 < 0.01$). In contrast, manual dexterity is strongly correlated with finger skin temperature at 40 msw ($r^2 = 0.84$), with dexterity deteriorating as a function of temperature.

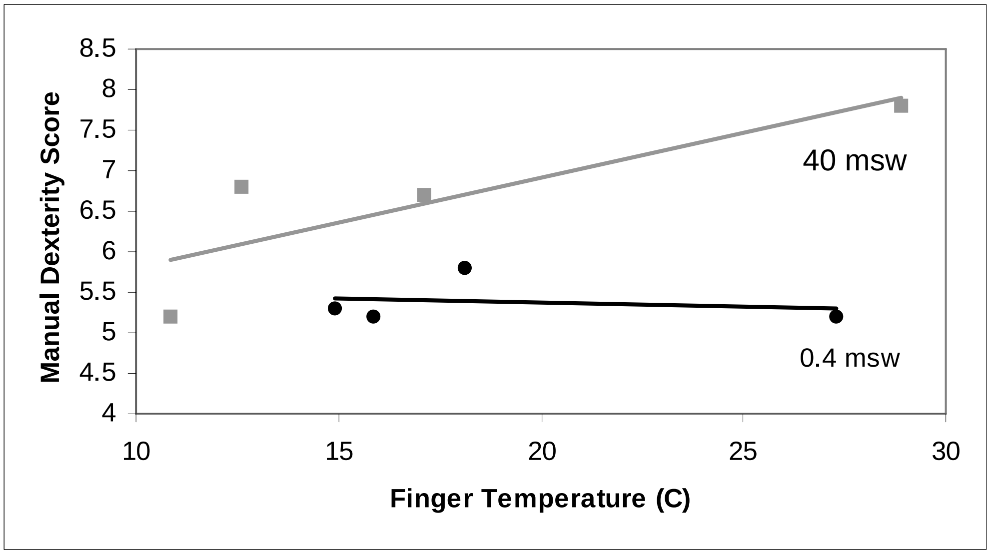

Figure 8: Manual dexterity versus temperature

Discussion

When wearing 3-fingered neoprene gloves in 4 °C water, divers' finger and hand skin temperatures decrease exponentially with time of exposure. This relationship can be modeled by an exponential equation of the form:

$$A\,e^{-kt} + B$$

This model indicates that when diving in 4 °C water, finger skin temperature will plateau at approx. 15 °C at 0.4 msw compared with 9 °C at 40 msw. Thus, at 40 msw, the neoprene gloves loose approximately 50% of their insulative value due to the effect of pressure. The gloves used in this study were made from Rubatex G-231-N neoprene. Results will likely differ, depending on the type of neoprene used.

From analyzing the two curves (0.4 msw and 40 msw) it is clear that the initial hand skin temperature is higher in the increased pressure condition. The difference probably results from the time interval required for pre-dive checks between completing the dressing of the divers and the divers putting their hands in the water at the start of compression. During this time the divers were wearing gloves in air and may have experienced a vasodilation effect. It is also notable that there is a relatively slow fall in finger skin temperature (and to an extent back of hand temperature) during the first four minutes of the 40 msw condition, followed by a rapid drop in skin temperature between minutes 4 and 6. The sudden drop in skin temperature coincided with the first test of grip strength and may result from a purging of residual air trapped within the glove by the force contraction of the hand when grasping the dynamometer. Subsequent smaller fluctuations in mean finger and hand skin temperatures may reflect some flushing action due to the dynamic movements required for grip strength and manual dexterity tasks. These effects are not present in the data at 0.4 msw. However, at 40 msw the compression of neoprene can be expected to affect the snugness of fit of the glove and make the hand more susceptible to flushing.

As pressure increases, neoprene deforms as the air bubbles within the rubber compress. Rubatex ® G-231-N is designed to resist compression. Other types of neoprene, which are more susceptible to compression, will likely provide less insulation at depth. Although this study did not model the loss of insulation with pressure, it is known that with increased pressure, the insulative protection of the neoprene decreases. MCM divers are capable of diving to 81msw, and the gloves will provide even less insulative protection at this depth.

Results show that the protective clothing worn by divers in this study was adequate to preserve the skin temperature surrounding the body core. The hand and fingers were most susceptible to heat loss. On average, chest and head skin temperatures dropped less than 3 °C after approximately 25 minutes of exposure. In contrast, mean finger skin temperatures dropped 11 to 13 °C at 0.4 msw and 18 to 20 °C at 40 msw. These results confirm that when wearing a dry suit and neoprene gloves, MCM divers are most susceptible to heat loss from the periphery, and that manual performance decrements in MCM divers are caused by local, rather than core cooling.

The components of manual performance are affected differently by finger and hand cooling. When wearing neoprene gloves, grip strength was unaffected by pressure or time of exposure to cold water. In contrast, exposure to cold water resulted in progressively lower tactile sensitivity scores, with no significant difference between the two pressure conditions. The decrease in tactile sensitivity was approximately linear with finger skin temperature. Manual dexterity was unaffected by exposure time or skin temperature at 0.4 msw, but manual dexterity decreased linearly as a function of skin temperature at 40 msw.

Of the three components of manual performance evaluated, tactile sensitivity appears to be the most sensitive to exposure to cold. These data support previous work completed by Schiefer *et al.,* (1984) and Vincent and Tipton (1988). The results also suggest that the effects of gloves and skin temperature on manual dexterity are not necessarily additive, but are dependent on glove thickness. The finding that manual dexterity is improved by pressure (compression of neoprene) and that tactile sensitivity is not was unexpected. Similarly the finding that tactile sensitivity is affected by skin temperature at 0.4 msw and that manual dexterity is not was also unexpected.

The results do not support the findings of Fox (1967) who suggest critical threshold theory for degradation in tactile sensitivity (12 to 16° C) and manual dexterity (8° C). Our findings suggest a continuous relationship between finger skin temperature and tactile sensitivity and manual dexterity over a range of 10 to 30° C, rather than a critical threshold (see Figures 6 and 7).

Results of the study show that there are more factors relating to the decrease in manual dexterity than finger temperature alone. At 0.4 msw, the divers showed no threshold for the effect of finger skin temperature. At 40 msw, manual dexterity appeared to decrease linearly with finger skin temperature over a range of 10 to 30 °C. However, there were insufficient data to confirm whether a threshold temperature existed at 20 to 22 °C as suggested by Vincent and Tipton (1988).

Although there is no loss of manual dexterity due to skin temperature cooling at 0.4 msw in warm water, manual dexterity scores were initially lower at 0.4 msw compared to 40 msw due to the thicker neoprene material. Thus, although protective gloves limit the drop in hand and finger skin temperatures, glove thickness will adversely affect manual performance and may outweigh the effect of cold (see Figure 8). This means that when designing equipment for divers, ergonomic guidelines must consider the compromises between the cumbersome effect of glove thickness and the degrading effect of cold. For example, results suggest that at 0.4 msw a thinner glove would improve manual dexterity at the expense of lower finger skin temperature and reduced tactile sensitivity.

It is concluded that 3-fingered neoprene gloves does not provide adequate thermal protection when divers are working in cold water. In addition, current, glove characteristics are not optimal for conserving both manual dexterity and tactile sensitivity ability of divers exposed to cold and pressure. A clearer understanding of the relationship between material properties and skin temperature and their effects on to manual dexterity and tactile sensitivity can lead to improved glove design.

The results of the study also have implications for the design of MCM diving equipment. Since MCM divers are capable of diving to depths of 81 msw, the insulation provided by the gloves will be minimal. Due to the lack of insulation provided by neoprene gloves, including Rubatex ® G-231-N, it is recommended that other materials and glove designs that provide the diver with more adequate insulation against cold should be investigated.

There are two main considerations for glove re-design: maintenance of manual performance capabilities; and protection from cold. The two components of manual performance that were affected by the gloves: tactile sensitivity and manual dexterity are affected by different characteristics of the glove. Tactile sensitivity is dependent on the properties of the glove over the area of the fingertip; how well the diver can sense through the glove material. Manual dexterity is affected principally in the regions of the glove that surround joint articulations.

Tactile sensitivity may be improved through redesigning the fingertips of the gloves to provide a more pliable material that is sensitive to local changes in pressure. Manual dexterity may be improved through designing gloves from a more supple material compared to Rubatex ® G-231-N neoprene. Alternately, modification to the physical design of the gloves could provide enhanced articulation over the joints of the finger and hand.

The overall thermal protection provided by the glove also needs to be addressed. A new strategy is required that will provide improved insulation of the hands throughout the dive. The diver is most susceptible to heat loss while on the bottom, and this is also the phase of the dive with the highest manual performance requirements. During the descent and ascent phase, manual performance requirements are reduced. A glove system could be designed to provide higher insulation when manual performance requirements are low. By doing this, hand temperature would be preserved thereby increasing the equilibrium temperature defined by parameter “B” in the cooling model described in Table 3. To properly evaluate new glove designs it is essential that diver manual performance capabilities be tested in realistic environmental conditions.

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The effects of exposure time, pressure and cold on hand skin temperature and manual performance when wearing three−fingered neoprene gloves (U)
Effets de la durée d’exposition, de la pression et du froid sur la température des mains et sur la dextérité d’une personne portant des gants en néoprène à trois doigts (U)

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J.B. Morrison; J.K. Zander

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(U) Cold water immersion and protective gloves are associated with decreased manual performance. Although neoprene gloves slow hand cooling, there is little information on whether they provide sufficient protection when diving in cold water. Nine divers wearing 3−fingered neoprene gloves and dry suits were immersed in water at 25 oC and at 4 oC, at depths of 0.5 msw and 40 msw in a hyperbaric chamber. Skin temperatures were measured at the hand, forearm, chest and head. Grip strength, tactile sensitivity and manual dexterity were measured at 3 time intervals. There was an exponential decay in finger and back of hand skin temperatures with exposure time in 4 oC water. Finger and back of hand skin temperatures were lower at 40 msw than at 0.5 msw. There was no effect of pressure or temperature on grip strength. Tactile sensitivity decreased linearly with finger skin temperature at both pressures. Manual dexterity was not affected by finger skin temperature at 0.5 msw, but decreased with fall in finger skin temperature at 40 msw. Results show that neoprene gloves do not provide adequate thermal protection in 4 oC water. Impairment of manual performance is dependent on the type of task, depth and exposure time.

(U) L’immersion dans l’eau froide et le port de gants de protection froids entraînent une diminution de la dextérité. Même si les gants de néoprène retardent le refroidissement des mains, il y a peu d’information permettant de savoir si ces gants assurent une protection suffisante lors d’une plongée en eau froide. Neuf plongeurs portant des gants de néoprène à 3 doigts et une combinaison étanche ont été immergés dans l’eau à 25 ºC et à 4 ºC, à des profondeurs simulées de 0,5 m et de 40 m en chambre hyperbare. La température de la peau a été mesurée aux mains, à l’avant−bras, à la poitrine et à la tête. La force de préhension, la sensibilité tactile et la dextérité ont été mesurées à 3 intervalles de temps donnés. Dans l’eau à 4 ºC, on a constaté une chute exponentielle de la température de la peau du dos de la main et des doigts en fonction de la durée d’exposition. À une profondeur de 40 m, la température de la peau des doigts et du dos de la main était inférieure à celle à 0,5 m de profondeur. La pression ou la température n’ont pas eu d’effet sur la force de préhension. La sensibilité tactile diminuait de façon linéaire par rapport à la température de la peau des doigts aux deux pressions. La température de la peau des doigts à une profondeur de 0,5 m n’a pas eu d’effet sur la dextérité, mais celle−ci a diminuée avec la chute de température de la peau des doigts à une profondeur de 40 m. Les résultats montrent que les gants de néoprène n’offrent pas une protection thermique suffisante dans l’eau à une température de 4 oC. La diminution de la dextérité dépend du type de tâche exécutée, de la profondeur et de la durée d’exposition.

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(U) underwater; diving; divers; immersion; dexterity; skin temperature; hyperbaric; grip strength; tactile sensitivity