UPPER LIMB COOLING: THE EFFECTS OF GENDER AND 5 DAY COLD ACCLIMATION ON STRENGTH, MANUAL PERFORMANCE AND PERCEPTION

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UPPER LIMB COOLING: THE EFFECTS OF GENDER AND 5 DAY COLD ACCLIMATION ON STRENGTH, MANUAL PERFORMANCE AND PERCEPTION

By

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Thesis Abstract

Substantial decrements in upper limb manual performance are evident following cooling of the upper limb in humans. In this thesis 2 studies were conducted to observe if gender (Study 1) or 5 days acclimation (Study 2) affected upper limb manual performance, strength and perceived pain and comfort both during and following whole arm immersion in 8ºC water. Performance and strength tests plus pain and comfort ratings of 6 males and 6 females were compared in Study 1 and six males in Study 2 were compared for the same tests and ratings on Day 1 and Day 5 of repeated whole arm 8ºC immersions. Study 1 showed no significant difference in muscle (T_{mus}) or skin temperature (T_{sk}) across gender. Relative to males, the females had significantly faster finger flexion and extension times ($p=0.03$), better peg and ring test performance during rewarming ($p<0.05$) and significantly lower maze tracking error rates ($0.008 < p < 0.02$). Comfort and pain ratings across gender were affected to a similar extent by cold immersion. In Study 2 during the 5-day acclimation, T_{mus} followed the same profile on days 1 and 5 of immersion. A significant Day by Time interaction ($p=0.04$) was evident for T_{sk} and the interaction was explained by significantly higher T_{sk} on Day 5 versus Day 1 prior to ($p=0.002$) and following immersion ($0.01< p < 0.02$). The 5-day acclimation gave a trend for ($p = 0.07$) faster finger extension and flexion times. Grip strength adjusted to pre-immersion values was significantly improved ($p =0.006$) by acclimation. As well perceived pain was significantly lower ($p < 0.05$) and comfort was significantly

higher ($p < 0.05$) during initial 20 min of limb immersion after 5 days of cold limb acclimation. In conclusion, with upper limb cooling females showed limited evidence of better manual performance relative to males for some fine and gross motor tasks. Five days of acclimation gave significant improvements in skin perfusion, as indexed by skin temperature, grip strength and cold perception during the initial immersion. Acclimation gave only trends for better performance on fine and gross motor tasks.

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I would like to thank Dr. Matthew White for his patience and wisdom, for which I would not have completed my thesis. From him I have learned much about the world of research, and as well much about myself and what one can achieve. Next thanks to my supervisor committee, Dr. Colin Higgs and Dr. David Behm, who have assisted immensely in attaining the completion of my thesis. My parents I cannot forget for blessing me with persistence and faith in myself. Thanks to my girlfriend, Shawnda, who has provided me with endless encouragement for my chosen course in life. As well, I would like to express my eternal gratitude to Duane Button, Kevin Power, and Amanda Hall, all good friends who helped me immensely along the path of this thesis. Thanks to my colleagues who worked with me in the Laboratory of Exercise and Environmental Physiology, Lise Petrie, Jon Power, Jeff Pope, Erin Bradbury, and Elena Alexandrou. Finally, I could not forget all my colleagues in the school of Human Kinetics and Recreation, and technical services (special thanks to Baxter Pope); whom without their help, guidance, and expertise this would not have been possible.

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List of Abbreviations

AD:M – Surface Area to Mass Ratio

ANOVA – Analysis of Variance

BF – Body Fat

CATT – Cold Air Tolerance Test

CIVD – Cold Induced Vasodilatation

CPAFLA – Canadian Physical Activity and Fitness and Lifestyle Appraisal

Co. – Company

FFA – Free Fatty Acids

HF – High Fat

HP – Heat Production

I_t – Total Body Insulation

LF – Low Fat

M – Metabolism

M_{shiv} – Shivering Metabolsim

MVC – Maximum Voluntary Contraction

SA/mass – Surface Area to Mass Ratio

SA/V – Surface Area to Volume Ratio

SBF – Similar Body Fatness

Tc – Core Temperature

T_{end} – Estimated end point of shivering

T_{es} – Esophageal Temperature

T_{mus} – Muscle Temperature

TSF – Total Skin-fold thickness

T_{sk} – Skin temperature

T_{ty} -Tympamic Temperature

T_{re} – Rectal Temperature

VO_2 – voluntary oxygen consumption

W – Watts

List of Definitions

Acclimation: Physiological adaptation to a variation in environmental factors such as temperature, climate, or altitude in an artificial environment (e.g. laboratory).

Acclimatization: Physiological adaptation to a variation in environmental factors such as temperature, climate, or altitude in natural environments (e.g. artic).

Amenorrhea: Absence or abnormal cessation of the menses. Can be induced by exercise, emotion or diet.

Beta endorphin (β-EP): A peptide consisting of amino acid sequence 61 to 91 of the endogenous pituitary hormone beta-lipotropin. Injection of beta-endorphin induces a profound analgesia of the whole body for several hours. The compound shows opiate-like activity.

Beta Liptropin (β-LPH): A lipotropin of the adenohypophysis of the pituitary gland that contains beta-endorphin as the terminal sequence of 31 amino acids in its polypeptide chain. Involved in the mobilization of fat from adipose tissue.

Bradycardia: Slowing of the heart rate, usually defined as a rate under 60 beats per minute.

Critical Water Temperature: the lowest water temperature a subject can tolerate at rest for 3 h without shivering

Eumenorrheic: Normal monthly menstrual cycles in a female.

Evaporative Heat Loss: heat transfer from the body to ambiance by evaporation of water from the skin and surfaces of the respiratory tract.

Hyperemia: The presence of an increased amount of blood in a body part or organ.

Interthreshold range: temperatures between the sweating and vasoconstriction thresholds that do not trigger autonomic responses. See Null Zone.

Lipotropin: Polypeptide hormone from the pituitary hypophysis, that is of particular interest because it is the precursor of endorphins, which are released by proteolysis. Promotes lipolysis and acts through the adenylyl cyclase system. Part of the ACTH group of hormones.

Lower Critical Temperature (LCT): The ambient temperature below which the rate of metabolic heat production of a resting thermoregulatory tachymetabolic animal must be increased by shivering and/or non-shivering thermogenesis in order to maintain thermal balance.

Metabolic Heat Production: Rate of transformation of chemical energy into heat in an organism, usually expressed in terms of unit area of the total body surface.

Null Zone: A range of core temperatures where sweating and vasoconstriction or shivering are not observed and thermoregulation arises only due to vasomotion. See Interthreshold Range.

Ponderosity: The property of being large in mass.

Plethysmography: measuring and recording changes in volume of an organ or other part of the body by a plethysmograph.

Plethysmograph: A device for measuring and recording changes in volume of a body part, organ, or whole body.

Second-Order Partial Correlations: Measure the linear relationship between two interval/ratio scale variables controlling for/holding constant a third interval/ratio scale ratio.

Set Point: A hypothetical set point used as a reference, or optimal body temperature against which actual body temperature is compared.
Shivering: Involuntary asynchronous tremor of skeletal muscles as a thermoeffector activity for increasing metabolic heat production.

Shivering Drive: Autonomic efferent nervous activity that elicits asynchronous skeletal muscle contractions subsequent to body cooling.

Shivering Fatigue: Progressively decreasing rate of metabolic heat production during continuous exposure to cold.

Sweating, thermal: A response of the eccrine sweat glands to a thermal stimulus.

Tachymetabolism: The high level of basal metabolism of birds and mammals relative to those of reptiles and other non-avian and non-mammalian animals of the same body weight and at the same tissue temperatures.

Thermal Tachypnea: A respiratory frequency accompanied by an increase in respiratory minute volume and, commonly, a decrease in tidal volume, in response to a thermoregulatory need to dissipate heat.

Thermogenesis, non-shivering (NST): Heat production due to metabolic energy transformation by processes that do not involve contractions of skeletal muscles.

Total Body Insulation: Insulation provided by various tissues in the body. The formula is given as I (°C/kcal/m^2 · hr) = (T_{re}-T_w)/(0.92 M ± S) where T_{re} is rectal temperature, T_w is water temperature 20 cm from the subject, M is metabolic heat production (kcal/m^2 · hr), and S is the loss or gain of body heat stores ($\triangle T_{re}$ · 0.83 · 0.6 · body weight) during final hour of immersion in kcal/m^2 · hr.

Upper Critical Temperature (UCT): The ambient temperature above which the rate of evaporative heat loss of a resting thermoregulating animal must be increased (thermal tachypnea or thermal sweating) in order to maintain thermal balance.

Vasoconstriction: reduction in the caliber of a blood vessel due to contraction of smooth muscle fibers in the tunica media.

Vasodilation: An increase in the caliber of a blood vessel due to relaxation of smooth muscle fibers in the tunica media.

Vasomotion: Change in caliber of a blood vessel.

Chapter 1 Thesis Overview

1.1 Thesis Overview

Extreme temperature environments have always provided a challenge for human survival. Offshore occupations such as the oil and gas industry or the fishery typically rely on workers being able to perform their given tasks efficiently and safely in cold environments. Often these workers have their hands immersed in cold water. Since the heat conduction of water is approximately 25 times greater than that of still air at the same temperature (1-3), cold water provides a large avenue of heat loss from the hands. The effects of cold water on the upper limb has been shown to cause a dramatic decrease in manual performance and strength (4). It has previously been shown that cooling of the upper limb, irrespective of the temperature of the body core, is responsible for the decrements in manual performance and strength (5). This shows when studying decrements in manual performance in cold environments there is a need to focus on the effects of cooling of the upper limb more so than whole body cooling (5). One of the gaps in the literature that became evident in this literature review (Chapter 2) was it is not evident if a gender difference is present with respect to upper limb cooling and performance. This is despite women such as the Ama divers have taken a predominant role in some offshore occupations where upper limb cooling is inherent (13). The possibility of a gender difference for upper limb performance after a local cooling was examined in the study in Chapter 3 of this thesis.

Another aspect of upper limb performance and cooling is that an acclimatization to cold has been shown to occur in both natives or non natives of cold climates (8-12).

Physiological changes apparent after limb cold acclimatization are increases in skin temperature and blood flow, plus decreases in the cold pressor response (7). Manual dexterity and upper limb strength are also known to be improved in workers from cold climates (8, 10). However, what became evident in the literature review of this thesis (Chapter 2) was that it is not known how long it takes to become acclimated to cold water immersion as would be indicated by better upper limb performance of manual or upper limb tasks after limb cooling. This was the study reported in Chapter 4 in this thesis; the nature and time course of cold acclimation of fine and gross motor tasks and of strength of upper limb.

A third aspect of upper limb cooling and manual performance in the cold is the presence of pain and discomfort especially during cold water immersion. It has been shown that males and females have different means of dealing with pain with males concentrating on the cause of the pain and females on the emotion caused by pain (6). As well, it seems that males will not pay much attention to minor pain while female see minor pain as a monitor of health and potential symptom of injury, illness, or disease (14). In Chapter 3, which examined gender, upper limb cooling and performance, perceived comfort and pain ratings were collected from the subjects. This was to assess if there are gender differences in these ratings (Chapter 3). Likewise in Chapter 4 of this thesis, perceived comfort and pain ratings were collected over a 5 day period of daily limb immersion in cold water. This was to assess if and when these ratings change over time during a cold acclimation (Chapter 4).

1.2 Co-Authorship Statement

i) Design and identification of the research proposal

Michael Powell and Dr. Matthew D. White were responsible for the study design and identification of the research topic.

ii) Practical aspects of the research

The data collection for the study in this thesis was primarily by Michael Powell. The data collection was in Dr. White's laboratory using his data acquisition system and the manual dexterity equipment that he had specifically constructed for these experiments.

iii) Data analysis

Michael Powell and Dr. Matthew White worked together to complete the data and statistical analysis for the study in this thesis.

iv) Manuscript preparation

Michael Powell prepared the first draft of the manuscript and each section of this thesis. Dr. White gave extensive feedback and corrections on the manuscript and on each section of the thesis.

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Chapter 2 Literature Review

2.1 Overview

This literature review begins with a section on how human body temperature is regulated, with a specific emphasis on regulation of temperature of the upper limb in the cold and differences in temperature regulation in the cold across gender. It will be demonstrated in the review that an exception to regulation of body core temperature within a narrow range (4), is that the temperature of the upper limb is poorly defended during cooling. Cooling of the upper limb is known to have extreme consequences on manual performance in cold conditions (16, 17). The decrease in manual performance arises mainly from a local cooling of the upper arm and this is evidenced by no further decreases in manual performance if the core temperature is lowered in addition to the arm muscle temperature (17). Several unanswered questions remain with respect to manual performance and upper limb cooling. This includes that females, such as the Ama divers (47), take part in occupations with inherent upper limb cooling, yet, an exhaustive literature review has not found studies examining comparisons across gender for fine and gross motor tasks following upper limb cooling. It remains to be established for groups such as the female Ama divers if they have physical or physiological advantages over males for this type of work with cool limbs in a cold environment. In this context, the effect of the female menstrual cycle on human body temperature regulation at rest and during exercise will be reviewed. In addition, it appears that humans demonstrate a local upper limb acclimatization or acclimation to repeated cold exposure (30, 32, 33) and this acclimatization is distinct from a whole body acclimatization to cold (31). The time to achieve such a local cold acclimation also remains to be established, as does the time course for adaptation of comfort and pain perception that is known to occur with repetitive upper limb cooling (30, 33). Finally, this literature review is concluded with a research hypothesis and testable questions that were addressed in the two studies on upper limb cooling as included in this thesis.

2.2 Overview of Human Body Temperature Regulation in Cold Environments

Regulation of Human Body Temperature

Hammel and colleagues (24) suggested that the two types of temperature sensitive neurons in the anterior hypothalamus defend a set-point of temperature regulation in a thermostatic model of human temperature regulation. In their model, one set of warm sensitive neurons sub-serves sweating and vasodilatation and inhibition of the effector neurons sub-serves shivering and heat conservation through vasoconstriction. The second set of cold sensitive neurons sub-serves shivering and vasoconstriction plus they inhibit neurons that act to dissipate heat. It was reasoned that deviations from a central set-point temperature are compared to a hypothesized and un-measurable stable central reference signal. Efferent impulses from the hypothalamus in the model are generated proportionally to the difference or error between stable central reference signal and the actual body core temperature. Collectively the system is described as a negative feed back model with an adjustable set point; elevations and decreases in skin temperature were also shown to influence the set point or core temperature that is defended (3). Satinoff (49) agreed that if there is a difference between the actual body temperature and the set point, an error signal is generated and this activates heat loss or heat production mechanisms to return the actual body temperature closer to the set point. A global explanation of the neural organization of mammalian thermoregulation is given by Satinoff (49). After the destruction of the anterior hypothalamus, behavioral thermoregulation survives and there are many areas of the brain caudal to the anterior hypothalamus containing temperature sensitive neurons that continue to contribute to thermoregulation. These structures include the posterior hypothalamus, midbrain reticular formation, and medulla. The "set point" theory of temperature regulation, as proposed by Hammel and colleagues (24) in non-human mammals, is supported by Cabanac and Massonnet (9). They found continuous thermoregulatory responses for humans warmed to a hyperthermic state in 38°C water, and then cooled in 28°C water to hypothermic conditions (9). Their results supported that thermoregulatory responses of the body to core temperature changes are continuous and always present. These responses include either heat loss responses, that is, sweating and vasodilatation, or heat generation/conservation responses, including shivering and vasoconstriction.

In contrast to the "thermostat theory" of human temperature regulation, more recent studies have supported existence of a "null zone" of core temperatures. Mekjavic and colleagues (40) found that subjects warmed by head-out-exercise on an underwater cycle ergometer in 28°C water, who were then passively cooled in the same bath, had core temperatures at which sweating ceased and shivering commenced that were significantly different. This illustrated for the first time in humans the existence of a thermoregulatory "null zone" between the core temperature thresholds for shivering and sweating. A study by White and colleagues (59) passively heated subjects in 40°C bath followed immediately by passive cooling in 30.6°C bath. Their results confirmed that there was a null zone of core temperatures where shivering and sweating did not occur. A later study by Lopez and colleagues (35), where males and females were warmed by forced-air warmers until sweating was induced and then cooled via central venous infusion of lactated Ringer's solution (~3°C), also confirmed the study by Mekjavic and colleagues (40). Lopez and colleagues (35), showed an inter-threshold range of core temperature of ~0.2°C where sweating and vasoconstriction were also not evident plus that women defend a higher inter-threshold range than men.

Human Body Temperature Regulation in Cold Environments

Exposing the body and limbs to cold during work impairs the efficiency and amount of work that can be completed (16, 17, 25, 39, 41, 43, 53). How exactly the body reacts to a cold air or a cold water environment is an area of ongoing research. Cold exposure of the body and especially the limbs is evident in the offshore industries in the North Atlantic Sea where cold, harsh work environments prevail for many months each year.

In response to cold there are two main mechanisms to produce heat, shivering thermogenesis and non-shivering thermogenesis. Non-shivering thermogenesis involves release of hormones that increase metabolic activity (36). Epinephrine increases the rates of glycogenolysis in liver and skeletal muscles and metabolic rate of most tissues while thyroxine increases catabolism of carbohydrates and other nutrients. Recent work shows that non-shivering thermogenesis involves beta 3 receptors and expression of at least 3 uncoupling proteins that initiate release of energy from human tissues (22); potentially this is an additional mechanism of non-shivering thermogenesis and body warming in humans. Shivering is a response of the human body to decreased core and/or skin temperatures where involuntary asynchronous contractions of agonist and antagonist skeletal muscles generate heat to help maintain body temperature (5). If the heat-production center in the hypothalamus is overly active, due to decreased body temperature, shivering is initiated when the tone of the muscles reaches a point when it elicits brief oscillatory, asynchronous contractions. Shivering can increase the generation of heat by ~400 percent (36). The degree or amount of shivering follows from the proportional control component in Hammel and colleagues (24) set point model of temperature regulation. A greater decrease in body temperature gives a more vigorous shivering response. In the anterior, preoptic area of the hypothalamus, heat gain and loss are also regulated with efferent impulses that are sent to peripheral blood vessels (36). Constriction of the vessels allows for heat conservation and dilation of the vessels for heat loss. In the cold, heat produced by the shivering muscles warms the deep vessels where blood has been shunted by a peripheral sympathetic vasoconstriction control.

Whole human body temperature regulation as described above, differs across gender. The next sections examine how female and male body temperature regulation differs in cold environments. First the effect of the menstrual cycle on temperature regulation in the cold is given.

2.3 Gender Differences in Thermoregulation in Cold Environments

Effects of Menstrual Cycle on Thermoregulation in the Cold

Glickman-Weiss and colleagues (18) evaluated the influence of gender on central thermosensitivity and heat production (HP) during cold water immersion. During the menstrual cycle, they reported the lowest T_{sk} was in days 2-6 of the follicular phase and the highest T_{sk} was on days 19-24 in the luteal phase. In the baseline condition, prior to water immersion, despite these differences in T_{sk} through the menstrual cycle there were no significant differences in T_{sk} across gender. As well, during cold-water immersion no differences were observed in T_{es}, across gender. Heat production (HP) when expressed as a function of surface area was, however, significantly lower during the cold immersion for females than for males. Glickmann-Weiss and colleagues (19) conducted a second study examining if differences in thermal and metabolic parameters occurred between gender during a 5°C cold air tolerance test (CATT). They also examined central thermosensitivity (β) in a cold-water (20°C) immersion trial (CWT) and assessed correlations between heat production during the CATT and CWT. For CATT there was no difference in heat production, tissue insulation, and T_{sk} with respect to gender. Thermosensitivity during CWT also showed no correlation with that during the CATT. They concluded that this lack of difference across gender might have been in part due to morphological differences across gender. Females during both menstrual cycle phases had higher T_{es} than males throughout the CATT and this followed since females had significantly higher body fat levels than males. This adiposity potentially provided greater insulation than for the males and this helped keep the females T_{es} elevated. It followed that a higher T_{es} would explain the lower heat production that they reported for the females in their study.

Viswanathan and colleagues (58) performed experiments on eumenorrheic and amenorrheic females, and males during rest and exercise in normal/warm (22°C) and cold (5°C) environments. They examined concentrations of beta-endorphin (β-EP) and beta-lipotropin (β-LPH) with a purpose to differentiate the β-EP and β-LPH responses across gender during the stresses of exercise and cold. As well, they explored the possibility that plasma β-EP and β-LPH responses to exercise and cold may differ in females with reproductive dysfunction. Beta-lipotropin is produced by the pituitary gland and promotes lipolysis. Beta-endorphin is a peptide sequence in β-LPH that acts as a neurotransmitter causing analgesia. Viswanathan and colleagues (58) found during rest at 5°C, males and eumenorrheic females had significant decreases in β-EP and β-LPH. Amenorrheic females, however, maintained pre-cold exposure levels of β-EP and β-LPH. After exhaustive work at 5°C β-EP and β-LPH were significantly increased in males and eumenorrheic females, whereas amenorrheic females maintained a constant low concentration. They concluded that plasma β-EP and β-LPH may reflect a thermoregulatory response to heat. A gender difference was also apparent in exercise- and cold-induced release of β-EP and β-LPH. As well, amenorrheic females may have an alteration in their response of the endorphinergic system to certain physiological states and this would influence their thermoregulation. Another study of females in the cold (20) illustrated menstrual cycle phase dependent thermoregulatory responses. Specifically in the luteal phase the rate of heat storage was decreased and surface heat flux was increased relative to the follicular phase.

From the studies discussed on the menstrual cycle it is evident that the female menstrual cycle should be considered in studies of female thermoregulation due to its potential influence on body heat balance. As a result it is important to study eumenorheic females in the same phase of their menstrual cycle when studying responses to cold across gender.

Shivering and Gender

Lopez and colleagues (35) found females had shivering triggered at higher core temperatures than males during rapid core cooling in air during their follicular phase. However, the inter-threshold range in females was not significantly different from that of males. Anderson and colleagues (1) conducted an experiment with males and females looking at their sweating and shivering responses after an exercise protocol with subjects immersed in 28°C water. They showed the onset of shivering was similar for males and females as well as suggesting a similar thermosensitivity across gender. Tikuisis and colleagues (54) also compared thermoregulatory responses across gender during cold-water immersion. When their males and females were grouped according to levels of body fat, no significant gender differences emerged in rate of rectal temperature cooling, in energy metabolism (i.e. shivering) and percent fat oxidation. This was despite that free fatty acids, glycerol, and beta-hydroxybutyrate were higher in the women. Their findings suggest that no gender adjustments are necessary for prediction models of cold response if body fatness and the ratio of body surface area to size are taken into account.

In summary of the findings on gender and shivering responses in cold environments, the literature shows some conflicting results. The shivering responses between genders may differ as reported by Lopez and colleagues (35) or may be similar across gender (1, 54). These discrepancies suggest the nature of whole body shivering responses across gender remains to be resolved.

Vasoconstriction and Gender

Lopez and colleagues (35) found that with core cooling, vasoconstriction core temperature thresholds were at significantly higher core temperatures in females as compared to males during cooling. Anderson and colleagues (1) found that males and females have a similar perfusion and appear to thermoregulate in similar manner in null zone of core temperatures when vasomotion is the only thermoregulatory response that is evident. Looking at the relative influences of skin and core temperatures to vasoconstriction thresholds in the cold Cheung, et al (11) saw T_{sk} contributed approximately 20% and core temperature approximately 80% of the input and the these contributions to skin blood flow were similar in males and females.

Again for thermoregulatory responses across gender in the cold there appears to be disparity in the literature. Some work shows a difference across gender (35) for vasoconstriction while other work shows no difference (1, 11). If vasoconstriction is at higher core temperatures for females as Lopez and colleagues (35) report this could cause an earlier decrease in blood flow to the upper limb and could diminish manual performance in the cold for females relative to males.

2.4 Gender Differences in Physique and Cold Exposure

Surface Area to Mass

Kollias and colleagues (29) studied the subcutaneous fat and surface area to mass ratio in subjects of varying levels of adiposity during head out cold-water immersion. For males and females of a given level of BF, the surface area (SA) to mass ratio for males, 2.3 m^2/kg, was significantly lower than females at 2.9 m^2/kg. This is because females, on average, have a smaller mass than males (2, 29, 37, 38). Thus, with a given level of BF, a decrease in mass will produce a higher SA/mass ratio for females. As a result for females of similar BF as males, faster female cooling was reasoned to be largely as a result of their higher SA/mass ratios than men (29). However, Kollais and colleagues (29) reported that there is a limit to this observation. When BF was above

30% both male and female have comparably low SA/mass ratio and maintained similar low values for heat production. The findings of Thompson and Hayward (53) in a study of 18 males taking part in a simulated 5 hour hike with 4 hours exposed to rain and wind, support Kollais and colleagues (29) findings. They found that males who had the highest SA/mass ratio cooled the fastest. White and colleagues (59) and Tikuisis and colleagues (54) report similar findings across gender, that higher surface area to mass is associated with faster cooling during warm or cold water immersion.

In summary of studies on SA/Mass and cooling (8, 29, 43, 44, 53, 54, 56, 59) it is evident that SA/mass ratio is an important determining factor with respect to the rate at which a person's core temperature decreases during whole body cold exposure. The SA/mass appears to predispose women to faster cooling than males of similar levels of body fatness (29). It should be noted from the study by White and colleagues (59) that cooling rates as a function SA/mass is an expression of weight$^{-0.58}$, since height was uncorrelated to body cooling rates and this indicated mass is the best predictor of cooling rates in cool water.

Body Insulation During Rest and Exercise during Cold Water Immersion

Bullard and Rapp (8) discussed a simple model for development of concepts of body heat loss in water immersion. Subcutaneous fat they contended only accounts for one to two-thirds of the total body insulation. Compared to rest, exercise increases the amount of exposed surface via movement of the limbs (21). Since heat exchange occurs at the surface, exercise causes an increase in heat exchange. Also, since un-perfused muscle is the major insulating portion of the shell (43, 56), when muscle is active it becomes perfused with blood and this affects the muscle's ability and that of the overlying fat to insulate the body (21). This provided backing for Hayward and colleagues (25) who stated in experiments on males and females in open water immersions, that exercise in cold water significantly increases the cooling rate of the body. The details of how insulation changes from resting to exercising conditions during cold-water immersion are given below in the studies of Veicsteinas and colleagues (56) and Park and colleagues (43).

Veicsteinas and colleagues (56) performed an experiment where male subjects performed up to 2 hours of mild, head-out immersed seated cycling exercise preceded and followed by 60 minutes of rest when thigh and over all body insulation were measured. Their results corresponded to that of Bullard and Rapp (8). They found that the insulation of the unperfused skin and subcutaneous fat accounts for only 10-15% during rest in water at critical water temperature and the remaining 85 – 90 % of insulation was due to poorly perfused, resting muscle. During exercise, however, Veicsteinas and colleagues ((56)) state that amount of insulation due to unperfused skin and subcutaneous fat increases to 40%, while that from muscle decreases during exercise in water. Park and colleagues (43) reported similar findings as that of Veicsteinas and colleagues (56). In their experiment they measured steady state insulation of males during rest and exercise for three hours. They found that skeletal muscle accounted for

75% of the total body insulation (I_t) at rest in water of a critical temperature or at the lowest temperature a resting individual can tolerate for 3 hours without shivering. The remaining 25% of the insulation was accounted for by subcutaneous fat and skin. During exercise, the insulation provided by skeletal muscle had diminished to 5 – 10% of total body insulation while insulation provided subcutaneous fat and skin did not diminish. Park and colleague's (43) findings suggest subjects immersed in tepid water have their heat loss controlled largely by blood flow to skeletal muscle with unperfused subcutaneous fat and skin providing a less important role than commonly supposed. However, they found that the maximum body insulation attained during rest in critical water temperature is linearly correlated with the subcutaneous fat thickness. Subcutaneous fat retards body heat loss in water of critical temperature not only due to the physical insulation of fat itself, but also due to its amplification of body insulation brought about by increased thickness of the muscle shell. This suggests that the insulative layer of muscle increases in persons with greater subcutaneous fat thickness. The more subcutaneous fat the person has the heavier the person will get, therefore, more strength is required to move this weight and thus more muscle is produced for this increased effort. Therefore, insulation depends more on a combination of subcutaneous fat and muscle, with muscle accounting for a majority of this insulation in resting conditions.

These results above indicate that tissue insulation or surface heat flux has an important role to play in human responses to cold conditions at rest and during exercise.

Choosing subjects of similar body composition is important when assessing changes in performance in cold conditions.

2.5 Limb Cooling and Manual Dexterity

Limb Cooling at Rest

Initially it was believed that insulation to cold temperature exposure was provided by mainly subcutaneous fat in the limb (44). In Petrofsky and Lind's (44) experiment on male subjects of varying BF, they studied altering muscle temperature by immersion of forearm in water from 7.5 to 40°C. They studied the effect of water immersion temperature on endurance of isometric handgrip contractions of 49% MVC and found that those with a higher amount of BF maintained isometric contractions for longer periods at lower temperatures. These results were attributed to the larger amount of BF. This observation was further supported when one subject who decreased in BF also had a decrease in isometric grip performance.

Giesbrecht and colleagues (17) performed immersions up to the clavicles in a body tank with a separate arm tank on the dominant arm in 3 different conditions; 1) cold body - cold arm, 2) warm body - cold arm, 3) cold body - warm arm. Before immersion, and at selected times during immersion, 6 tests of fine or gross motor movement tasks were performed. They saw that fine motor tasks decreased by 75% and gross motor tasks decreased by 54%. Cooling of the arm muscle temperature (T_m) was shown to account for 85-98% of the decreases in test scores. In contrast, the effect of core cooling had less of an effect only accounting for 4-10% of variance in four of the six tests. They concluded that during immersion hypothermia, that the decrements in finger, hand, and arm performance are due almost entirely to local effects of arm cooling, with fine motor tasks being affected more so than gross motor tasks.

In 1988, Vincent and Tipton (57) studied immersions of the hand only and the forearm only in males in 5°C water and its effect on grip strength. They concluded that both hand and forearm protection is important for the maintenance of grip strength during cold water immersions.

Limb Cooling During Exercise

Thompson and Hayward (53) simulated a 5-hour walk with 18 subjects at 5 km/h at 5°C with continuous exposure to rain at 7.4 cm/h and wind at 8.0 km/h over the final 4-hours. They assessed manual dexterity and grip strength. Only five of the subjects completed the entire protocol with rain and wind. They concluded that with the cold wet conditions there was a decrease in manual dexterity and grip strength. It might be reasoned that the problem with grip strength may be because shivering may cause some interference with the recruitment for testing grip strength. This is not so according to Meigal and colleagues (39). They took 6 males and exposed them to three conditions; 1) thermo-neutral air (27°C), 2) cold air (10°C), 3) cold air (10°C) with cold drink (8°C). Then subjects were tested for hand-grip strength, elbow flexion and shoulder flexion.

They found that shivering and voluntary output control could occur simultaneously; the motor system can recruit and effectively utilize thermoregulatory and motor functions at the same time.

For studies of manual dexterity and strength with limb cooling, Giesbrecht and colleagues (17) found that the core temperature does not have a significant effect on limb performance and, as such, cooling of just the limb itself is needed. Sendowski and colleagues (50) stated that cooling of larger areas (forearm and hand) would be the best method for studying general and local physiological responses of the arm, whereas for studying cold induced vasodilation (CIVD) (i.e "the hunting response") immersing the index finger alone would be the preferred protocol. Sendowski and colleagues (50) studied immersion of the dominant index finger, hand, or forearm and hand in 5°C water for 30 min. During cold-water immersion the vessels in the hand and fingers eventually alternate from being vasoconstricted to vasodilated. The physiological relevance of this response is apparently to prevent the occurrence of local cold injuries (50).

In summary of the studies on limb cooling and changes in manual dexterity and strength, it is evident subjects of similar body fatness or adiposity should be studied (44). In addition, for assessment of these performance changes, the entire limb should be immersed in cold water (50) Additional cooling of the core provide minimal decreases in manual dexterity and strength (17, 39).

2.6 Acclimation and Acclimatization to Cold

Acclimation versus Acclimatization

The reaction to prolonged, repeated cold exposure is of importance when looking at the effects of cold exposure. LeBlanc has shown in several studies (30, 32, 33) that an acclimatization to extreme cold conditions (i.e. in cold adaptation uncontrolled conditions, outside a laboratory) in native people is evident relative to control subjects not native to these environments. Thus when considering the effects of cold exposure in a cold offshore working environment, repeated exposure of a minimum of the hands to cold air and water is needed for an acclimatization to occur. In this thesis acclimation (i.e. in controlled laboratory conditions) to repeated upper limb cold-water immersion will be investigated. It is pertinent, however, to overview both acclimatization and acclimation, irrespective of where they occur, since both can effect limb cooling and performance.

Whole Body versus Local Acclimation or Acclimatization

In addition, to the differences between acclimation and acclimatization, there is also a difference with respect to the area of the body to which acclimation or acclimatization occurs. The studies on acclimation/acclimatization can be separated into two groups. The first is whole body acclimation or acclimatization, where the entire body is acclimated to cold (31) and the second is local acclimation or acclimatization that appears to be specific body parts, such as the hand and forearm. In local acclimation the rest of the body remains un-acclimated to the cold (31).

Whole Body Acclimation or Acclimatization

Whole body acclimation was confirmed by Skreslet and Araefjord (51) who studied three nonprofessional scuba divers doing controlled whole body cold water dives for approximately 30 minutes duration with a frequency of 4 times in 2 weeks. They suggested that there are three stages to acclimatization; 1) an un-acclimatized stage where cold stress is met by elevated metabolic rate compensating heat loss, 2) an intermediate stage where fall in core temperature is evident due to heat loss not fully compensated for by metabolism and thought to be caused by habituation of CNS, and 3) an acclimatized stage where constant core temperature is maintained due to increased VO_2. However, acclimatization effects disappear quickly when the exposures are discontinued after 17 days when the cold exposures were discontinued (51).

In the female Korean Ama divers whole body acclimatization is seen during cold-water dives. Hong (26) stated that both Korean males and female Amas previously dove for seaweed, abalones, snails, and sea urchins in all seasons. The males discontinued their participation in this underwater harvest, about 2000 years ago (26). During late spring and summer, males still dive, however, when it becomes colder only the females dive. Despite a lowering of their core temperatures, female Ama divers can suppress shivering which would normally cause an increase in heat loss due to blood perfusion to muscle (26, 43, 56). As well these female Ama divers are usually more muscular than female non-divers (26). As mentioned by Park and colleagues (43) muscle gives a higher insulation than fat, therefore, it could be postulated that higher musculature in Ama divers gives them better insulation than non-divers assuming their muscles are inactive and remain with a resting state of perfusion. Thus the suppression of shivering would economize body heat loss. In addition, Hong agreed with Paik and colleagues (42) by stating that female Ama divers have a more effective countercurrent heat exchange in the limb, in addition to their blunted shivering response and decreased total surface heat loss. Arterial blood perhaps is pre-cooled before it reaches the peripheral zone, thus reducing the thermal gradient (26) and heat loss from the Ama's limbs.

Similar findings were noted by Jansky and colleagues (27) studied head-out immersed male subjects in 14°C water for 1hr, 3 times per week for 4 to 6 weeks. Following this treatment they noted that there was an increase in vasoconstriction evidenced by the lowering of forehead, chest, forearm, and finger T_{sk}. As well, there was a shift of the shivering threshold to a lower core temperature. This was apparent after four successive immersions and increased with continuation of the experiment.

From the above studies, whole body acclimation occurs in 3 stages ending with an acclimatized state to cold-water exposure of the whole body. As well, females may have some innate ability to withstand whole body immersions in cold water through a better counter current heat exchange and possible pre-cooling of the blood in their limbs.

Finally, female Ama divers seem to be more muscular than non-divers providing more insulation via muscle tissue. However when muscle perfusion is increased during exercise, heat loss increases as muscle insulation decreases; even so the perfused, active muscle plus fat and skin still provide more insulation than insulation from plus fat and skin alone (56).

Local Cold Acclimation

Acclimation to local cooling of the hand and/or fingers causes an increase in blood flow and a decrease in the sensation of pain (30-33, 45, 46). Purkayastha and colleagues (45, 46) exposed both tropical (from India) and non-tropical men to the cold Arctic environment and found that tropical subjects could adapt to cold even though they were not originally from that area of the world. Many have stated (7, 13, 30, 32, 33) that in studies with Gaspé Fishermen and Eskimos, immersing a hand in cold water showed increased blood flow and better pain tolerance compared to manual workers and non-Eskimos who acted as controls in their experiments. When looking at the effects of cold water immersion of the finger (45, 46), their findings were similar to that of hand immersions discussed above (7, 13, 30, 32, 33). Their results suggest there is an acclimatization and improvement in manual dexterity with repeated immersions. The mechanisms underlying this acclimatization and time course of this acclimatization in manual dexterity with repeated immersions remain to be established.

With respect to blood flow changes in the arm, the nature of this acclimatization is disputed. Elkington (14), Gaskell and Long (15) and Leftheriotis and colleagues (34) argue against the finding of increased blood flow in the hand after acclimatization (7, 13, 30, 32, 33). Elkington (14) immersed 25 males' fingers in ice water for 1 hour in Antarctica and showed finger blood flow, estimated by strain-gauge plethysmography, decreased in colder months. They also reported that cold induced vasodilation (CIVD) became less as exposure to the cold over the year progressed. Gaskell and Long (15) saw no changes in hand blood flow by venous occlusion plethysmography while one hand was immersed in 4°C water for 1 h per day, 5 days/week for 3 weeks and the opposite hand was immersed in 32°C water. Leftheriotis and colleagues (34) studied locally acclimated verses non-acclimated male responses to limb arterial occlusion via venous occlusion plethysmography during either 5 minutes of arterial occlusion, 5 minutes of sustained handgrip (10% MVC), or both treatments simultaneously. This was followed by 5 minutes of immersion of their forearm in 5°C water after which tests were repeated. They found that subjects locally cold-acclimated their forearm and finger and showed decreased vasodilatory responses only when exposed to cold.

However, there may be an explanation for these discrepancies on the existence or non-existence of increased blood flow following a local cold acclimation. In Elkington's experiment (14) blood flow was reduced compared to other reports of increases in blood flow (45, 46, 48). This may have been since Elkington's (14) subjects were exposed on average to 42 days in very cold conditions for long periods of time may have caused whole body acclimatization to cold that overrode the local acclimatization to the fingers. This follows with the findings of Bridgman (6) in tests of index finger immersion in cold water (0 to 0.3°C) between divers versus non-divers in Antarctica. He reported that with whole body acclimatization, local peripheral acclimatization effects are overridden. As well, Gaskell and Long (15) study's protocol had each subject wearing polyethylene gloves (0.001mm thick) to prevent water absorption via the hands. No change in the relative flow rate of blood in the two hands from cold exposure was found, and thus no acclimation to cold. However the gloves may have reduced heat flux from the hand since the glove provided insulation and thus reduced the cold stress and possibly the extent of the acclimation. The water immersion of the opposite hand in 32°C water may have caused heat gain by the subjects since water's heat conduction is approximately 25 times greater than that of still air (8, 10, 12). Therefore, even though the hand was in warm water some heat may have been lost or gained via conduction.

From the above findings on acclimation or acclimatization to cold (7, 13, 15, 17, 30, 32-34, 45, 46), it appears that the effect on the upper limb to repeated cold immersion, or acclimation, depends on the degree or depth to which the limb is immersed. This agrees with the differences seen in studies on whole body cooling (26, 27, 42, 51) versus limb cooling up to the level of the forearm (34). This also agrees with differences seen in studies cooling the upper limb up to the forearm versus only the hand or finger where more CIVD occurs in finger immersion than forearm immersions (31, 45, 46). The more the core is cooled, the less blood flow there is to the extremities. This prevents decreases in core temperature since whole limb cooling produces intense vasoconstriction. Thus with cooling of the entire upper limb, the blood flow to the hand and fingers is decreased, which is the opposite effect of only cooling the finger(s) or hand.

2.7 Pain and Comfort on Cold Exposure

Many studies (7, 13, 30-33) have shown that exposure to cold environments causes some degree of pain and discomfort. This section reviews pain and comfort perception in cold environments with respect to gender differences, and acclimation or acclimatization to cold induced pain and discomfort.

Gender Differences in pain and Comfort on Cold Exposure

In a review by Unruh (55) on gender variations in clinical pain experience, females were stated to be more likely to have persistent and recurrent pain due to chronic, however, not life threatening diseases. She went on to propose that to females, pain is a monitor of health and potential symptom of injury, illness, or disease. Thus from this, females appraisal of pain would incorporate multiple features of pain to assist in separation of pain due to normal biological processes and pain due to other potentially pathological sources (55). Males in contrast, according to Unruh, have recurrent pain of lesser intensity, frequency, and duration than women. However, males are more likely to experience pain from injury, and acute and chronic life threatening diseases (55). Due to these factors, males may be less likely to attend to mild or moderate pain since it may be insignificant. If this pain is associated with other factors such as pain or genital pain, males may perceive this as a more serious type of pain and if not it would be perceived as a challenge (55).

Keough and Herdenfeldt (28) examined if gender differences would be found when looking at the effect of sensory-focused and emotion-focused coping instructions on cold pressor pain experiences. The cold pressor test consisted of placing the subject's non dominant hand in an ice water bath maintained at a temperature of 1-2°C for as long as possible. For safety reasons, there was a time limit of 2 minutes although this time limit was unknown to the subjects. They found that males showed less negative pain responses when compared to females when focusing on the sensory component of pain. When females used sensory-focused coping, they reported lower pain scores than compared to emotion-focused coping. They stated as well that females use emotion-focused coping rather than sensory-focused coping and this had detrimental effect in terms of their subjective experience of pain. When comparing emotion-focused coping across gender, males experienced less pain that females. Supporting this study, Zeichner and colleagues (60) found that females had increased physiological arousal during a cold pressor test, however, across gender they rated pain similar to that of men. This study highlights the different ways men and women cope with cold induced pain and the effect on their responses to acute pain.

Learned Pain Tolerance

Hall and Davies (23), they studied possible gender differences between athletes and non-athletes across gender on measures of perceived intensity and affect of pain to a cold-water pressor test. The intensity scale provided a measure of perception of strength of pain stimulus, whereas the affective magnitude was a measure of perception of how the pain feels. Non-athletic females reported significantly higher pain intensities than the other three groups (non-athletic males, athletic males and females). As well, non-athletic females showed significantly higher responses on pain affect. Compared to non-athletic males, however, they did not significantly differ. In comparing the males alone, non-athletes perceived significantly higher affects of pain than athletes. Both non-athletic groups perceived the affect of pain greater than intensity, whereas athletes perceived intensity of pain greater than perceived affect. These findings supported their hypothesis that pain tolerance may be able to be socially learned, depending on type and frequency of pain experiences. This can be viewed in the light of a different setting as well. Offshore workers would be less likely to perceive pain due to hand immersion in cold water as greatly as onshore workers due to adaptation and the social aspects of offshore work.

Along the same lines as the study above, Sternberg and colleagues (52) conducted a study evaluating pain sensitivity from noxious cold pressor test in males and females athletes 2 days before, immediately following, and 2 days after competition. Non-athletes were used as controls during the same times that athletes were tested. They found that immediately following competition, athletes rated pain less intense and less unpleasant compared to 2 days pre and post competition. No differences in pain sensitivity during cold pressor tests were seen in 2 days pre and post competition in athletes or non-athletes. However, the non-athletes had no differences in pain throughout the whole experiment. In comparing offshore workers and the subjects from the above experiment, offshore workers are constantly being exposed to cold water immersion and working for longer periods of time than athletes play a game. Though there may be periods during work in an offshore environment that are very stressful and require intense concentration, which may allow for a decreased perception of pain to cold water. So it can be concluded that training state to a certain condition, in this case cold exposure, can reduce the perceived pain from the condition. As well, in stressful conditions, sport competition or dangerous work environment may cause a decrease in perceived pain.

Acclimatization or Acclimation to Cold Induced Pain

Cultures that are exposed to cold environments with respect to the extremities, also seem to have an increased pain tolerance to cold exposure. Brown and colleagues (7) and Egan (13) performed cold water and air exposures, respectively, with Eskimos and a control group in the artic. Each study found that the Eskimos had an increased pain tolerance to the exposure. Brown and colleagues (7) even had three of their Eskimo subjects fall asleep during the exposure. LeBlanc (30, 32, 33) studied cold water immersion of the hands of Gaspé Bay fishermen and controls. Each study found that while the controls found the immersion unpleasant and painful, with three having a fainting reaction, the Gaspé Bay fishermen retained "a joyful mood" throughout the experiment. So it seems that with prolonged exposure due to culture and living environments, one may become adapted with a reduced reaction to the pain associated with cold water immersion compared to control subjects in all of the above studies

2.7 Summary of Literature

It is apparent that there are no studies that examined gender differences in manual dexterity and strength following upper limb cooling. A classic case is that of the female Ama divers. According to Hong (26) both men and women Ama took part in diving work at the beginning of this type of undersea harvesting. Males, however, dropped out of the occupation in the cold seasons about 2000 years ago. Females have continued in the harvest in the cold seasons. The reason or reasons for this preference of females for this type of cold-water work is not evident. It does seem that females have adapted to diving in cold water more so than males, thus no males are used during seasons where the water is cold. What physical, physiological, or psychological reasons for this apparent selection of females for work in cold-water environments remains to be determined.

It is evident that there is an acclimatization to limb cooling and that manual performance as well as pain and comfort ratings appear to improve after repeated exposure of the limbs to cold. The nature and time course of this acclimatization is not evident in the literature.

2.8 Research Hypothesis

Hypothesis 1: Based on the review of the literature, including evidence from the female Ama divers, it is hypothesized females will perform better on manual tasks with limb cooling than males. It is also hypothesized that perceived pain and discomfort will be higher in females than males.

Hypothesis 2: It is hypothesized that after a 5-day acclimation to upper limb cold-water immersion, there will be significantly improved strength and performance on fine and gross motor tasks. Perceived pain and discomfort are hypothesized to be lower after 5 days of acclimation.

2.9 Testable Questions

Gender Comparison

1. Is there a gender difference in fine and gross motor task performance during and following 75 minutes of cold-water immersion of the dominant upper limb?

2. Is there a gender difference in perceived pain and comfort during and following 75 minutes of cold-water immersion of the dominant upper limb?

Local Acclimation to Cold

1. For males after 5 days of acclimation, is there a difference in fine and gross motor task performance during and following 75 minutes of cold-water immersion of the dominant upper limb?

2. For males after 5 days of acclimation, is there a difference in perceived pain and comfort during and following 75 minutes of cold-water immersion of the dominant upper limb?

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Chapter 3: Effect of Gender on Fine and Gross Motor Tasks During and Following Upper Limb Cooling

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3.1 Abstract

Limb cooling is known to significantly decrease manual dexterity and strength. It is unknown, however, if male and female upper limb strength and manual performance on fine and gross motor tasks have similar decreases with limb cooling. In addition, it is also not clear if there is an equal perception of cold across gender with limb cooling. Six males and 6 females of normal physique volunteered to undergo upper limb cooling in 8°C water for 75 minutes followed by 60 min of rewarming. Prior to the cold immersions a 18 mm, 22-gauge thermocouple was placed under a local anesthetic (2% lidocaine) in the lateral aspect of the biceps brachii. Prior to, during, and following the cold-water immersion, evaluations were made of grip strength, fine and gross motor task performance and perceived comfort and pain. No significant differences in muscle (T_{mus}) or skin temperature (T_{sk}) were evident across gender. For all subjects cold immersion significantly decreased performance for the fine and gross motor tasks and hand grip strength. The females gave significantly better performance than the males for hand flexion and extension ($p=0.03$), for a peg and ring task during rewarming ($p<0.05$) and for maze tracking error rates ($0.008 < p < 0.02$). Comfort and pain ratings were significantly affected by cold immersion to a similar extent across gender. In conclusion, on selected fine and gross motor tasks females performed significantly better than males but they gave the same ratings of comfort and pain prior to, during and following upper limb cold immersion.

Keywords: cognition, cold, fine and gross motor tasks, gender, manual dexterity

3.2 Introduction

An important but little studied topic on survival in the cold is the large and significant decreases in manual dexterity and strength with upper limb cooling (4, 6). Substantial decreases in fine and gross motor tasks performance are evident after cooling of upper extremities in cold air (12) and cold water (4, 6, 19). These large decreases in fine and gross motor tasks performance (4, 6, 19) induce significant performance decreases in life saving tasks, such as those needed in offshore safety vessels. Therefore, it is important that influences on upper limb performance during cold exposure are identified so that survival can be improved during cold exposure. One possible influence on upper limb performance during cold exposure is gender.

It is striking to note that in occupations with inherent limb cooling, such as in Ama pearl diving (13, 17), female divers have been preferentially selected over males over the last 2000 years (13, 17). It is not entirely apparent why female Ama have been naturally selected for this occupation (13, 17). Females generally have a lower surface area to mass ratio (SA/mass ratio) that should help them to cool more slowly and to function better in cold water, however, the larger *total* amount of muscle and fat in males would suggest that they should be less affected by cold water immersion and better suited for work in these environments than females (1, 14, 15, 18, 20).

Two possibilities to explain why females such as the Ama divers may function better than males in cold work environments (13, 17) are that they could either have better upper limb performance with upper limb cooling or a decreased cold induced pain for a given cold stimulus. An exhaustive literature review did not however uncover any comparisons across gender for manual dexterity and strength changes after limb cooling. Also the literature was not clear if there was a gender dependence of cold perception (9-11, 21).

As such this study was conducted to examine if with upper limb cooling there are gender differences for manual dexterity and strength. Two specific questions were asked in the study. The first question was to assess if similar degrees of upper limb cooling across gender gave similar decreases in manual dexterity and strength. The second question was to assess if comfort and pain levels during and following arm only cold-water immersions were gender dependent.

3.3 Methodology

3.3.1 Subjects

With permission of the ethics committees at Memorial University and Dalhousie University, 12 subjects (6 males, and 6 females) of normal physique and college age participated in the study after having read and signed an informed consent form. The sample size was determined using a power calculation. The difference worth detecting was set at 5% with an alpha level of 0.05 and with a beta value of 0.8 and a standard deviation of 10% of the projected means (6). The subjects were instructed to abstain from alcohol, caffeine, or medication for a period of 24 hours before participation. Their dress consisted of shorts and a T-shirt or tank top.

3.3.2 Instrumentation

A 18 mm, 22-gauge thermocouple (Mon-a-therm Myocardial, Mallinckrodt Med Inc., St. Louis, MO, USA) was inserted into the lateral aspect of bicep brachii in the dominant arm. Copper-constantan thermocouples were taped on the surface of the hand of the dominant arm as an index of skin temperature (T_{sk}). These probes were secured to the skin with Elastoplast waterproof tape (Smith + Nephew). The temperatures were collected by a data acquisition, LabVIEW (National Instruments, Austin, TX).

Manual Dexterity and Strength Tests

A series of 7 tests were constructed to measure fine and gross motor performance of the dominant arm. Prior to the actual experiment, training on the performance tests was conducted over 5 trials or until a plateau in performance was evident. The tests and the order they were preformed are as follows:

Finger flexion and extension: Subjects closed and opened their dominant hand as rapidly as possible (dynamic movement) five times with their hand held at arm's length. Time was recorded at the commencement of the exercise by the experimenter and ended when subject completed the final extension (6).

Grip Strength (modified from Canadian Physical Fitness and Lifestyle Appraisal (CPFLA) protocol for Grip Strength): A hand dynamometer (Takei Instruments Co., Japan, Grip D [Digital Hand Grip Meter]) was placed in the hand with the grip of the dynamometer placed so the second joint of the index finger fits snugly under the hand and takes the weight of the instrument. It is held in line with the forearm at thigh level away from the body. The seated subject then squeezes vigorously, exerting maximum force (kg: 0 to 100kg ± 2.0kg, measured to 0.1kg), and exhales.

Finger Dexterity Test: This test was included a task of picking up the smallest of 19 cylinders and discs with a diameter of 2.5 cm, and ranged in length/width from 30 mm to 0.25mm. Those that had a length from 30mm to 4mm were considered cylinders, and those below (2mm to 0.25mm) were considered discs. The subjects were seated, and proceeded to attempt to pick up the cylinders and discs. The size of the smallest disc that could be picked up was recorded. The test similar to that in (6).

Peg and Ring Test: Six pegs (2 cm in diameter, and 4 cm in length) were fixed on to a board (30.5 cm by 30.5 cm) arranged in two rows of three from top to bottom. The pegs in each row were spaced 5 cm, and the rows were spaced by 10 cm. A larger peg (2 cm in diameter, and 9 cm in length) was place at the top of the board for starting placement of the rings (4 cm outside diameter, 2.5 cm inside diameter). The subjects were seated, and commenced at the signal of an experimenter. The time taken to place one ring on each peg (one at a time) and then replace them (one at a time) back to the start peg was recorded, The test was similar to that in (6).

Nut and Bolt Test: A board (45 cm by 45 cm) having four bolts fixed to it (7mm diameter, 18mm in length). At the top of the board was a container holding the four nuts (12mm outside diameter, 6mm inside diameter, 6mm high) to be fitted on to the bolt. Bolts were arranged in a square (8 cm sides). The subjects were seated, and commenced at the signal from an experimenter. The time to fit all four nuts on the bolts was recorded. The test was similar to that in (6).

Maze Test: The subjects were instructed to navigate through a maze with the probe as fast as possible and with the least number of "hits" (hitting the probe off the side of the maze; counted via a counter and emitted a beep) as possible. At the signal of the experimenter the subjects commenced and the time taken to navigate to the end, and the number of "hits" were recorded. The test was similar to that in (6).

Movement and Reaction Time: Reaction time is measured via a Multi-choice Reaction Timer (Lafayette Instrument Co.) and movement time is measured via a Stop Clock (Lafayette Instrument Co.). Subjects were seated and placed their fingers on the start button. When the stimulus light (Lafayette Instrument Co.) turned on, the subject, moved their fingers from the start to the finish button (buttons 60 cm apart and each encased in a waterproof 10 cm^3 plexiglass cube). Movement time was recorded as time from the Stop Clock minus time from the Multi-Choice Reaction Timer, and reaction time was recorded from the Multi-Choice Reaction Timer. The test was similar to that in (6).

Arm Cooling

Subjects sat in a height adjustable chair so as to allow the subject a comfortable height to immerse their dominant arm to the level of the axilla. The arm tank was constructed of PVC tubing 95 cm in depth and 22 cm in diameter, insulated with ARMORFLEX. An Endocal Refrigerated Circulating Bath (NESLAB, Portsmouth, NH) was used to cool the water entering the tank. The inflow tube from the bath to the tank diverged into two insulated (ARMORFLEX) tubes (84 cm in length) connecting and depositing the chilled water into the top of the tank via 12, 1 cm holes located 13 cm down from the top about the circumference. An outflow tube was located at the bottom of the tank and connected to the bath via another tube. The temperature of the water in the arm tank was observed via LabVIEW (National Instruments, Austin, TX) and a thermometer (Brannan, England) monitored the water temperature of the NESLAB bath. Maintenance of temperature was done via the NESLAB's bath's temperature dial (min - 30°C and max 100°C) and addition of ice to the arm tank. Flow from the bath to the arm tank was controlled via a dial on the bath; the water level could not exceed a set level in the bath because of the risk of overflowing the bath, which limited the flow rate of the bath. The water temperature for this experiment was set to 8°C.

3.3.3 Protocol

A medical doctor was present each day for local anaesthetic (2% lidocaine) and insertion of a 22-gauge thermocouple in the lateral aspect of the dominant arm's bicep to measure muscle temperature (Tmus). This site was chosen since it represents a considerable muscle mass of the arm well distant from major vessels or nerves as stated by Giesbrecht and colleagues (6)

After thermocouples were inserted in and on the subject's dominant arm, the first series of tests were performed without arm immersion. Subjects then immersed their dominant arm in 8°C water for 75 min followed by 1 hour of recovery.

The times that the tests were done during immersion were at 15, 45, and 75 min from beginning of immersion. At the beginning of a trial the subject would remove their arm from the tank and then place their dominant hand in the starting position on a table next to them with all test materials. After completion of the trial, the subject's dominant arm was re-immersed. At the end of immersion, subjects removed their dominant arm and which warmed passively in the ambient air for an hour with 4 test trials at 90, 105, 120, and 135 min of the experiment. Each test battery took about 3 or 4 minutes.

The time of day each subject took part was kept at similar times for each trial during pre-immersion orientation trials. Though according to Castellani and colleagues (2), vasoconstriction is not affected by the time of day.

Pain and Comfort Ratings

A subjective rating of pain and comfort was made employing the scales developed by Havenith and colleagues (8). The scale for comfort was from +2 (Comfortably Warm) to-10 (Extremely Cold). For pain the scale employed was from +1 (No Pain) to +11 (Unbearably Painful).

3.3.4 Statistical Analysis

A two-way ANOVA with a non-repeated factor of GENDER (Levels: Male and Female) and repeated factor of TIME (Levels: 0, 15, 45, 75 90, 105, 120, and 135 min) was performed to establish the effects of cooling on test performance and body temperatures. A similar two-way ANOVA was employed for comfort and pain ratings during cold limb immersion. In the comfort and pain ANOVA the factor GENDER was employed and to account for the rapid changes in comfort and pain on cold limb immersion the factor TIME included more levels (0, 5, 10, 15, 20, 25, 30,45, 75 90, 105, 120, and 135 min) in the first 30 minutes of immersion. The level of significance for these analyses was set at 0.05.

3.2 Results

Muscle Temperature (T_{mus}) and Hand Skin Temperature (T_{sk})

From pre-immersion until the end of immersion at 75 minutes, T_{mus} significantly dropped by approximately 50% and no significant differences (F_{gender}= 0.98, p =0.35) were seen across gender (Fig. 3.1a). After immersion T_{mus} increased in a non-linear manner to a level of about 26°C at the end of the rewarming period at 135 min.

Prior to, throughout, and following immersion (Fig. 3.1b) there were no significant differences across gender (F_{gender}= 0.10, p =0.75) for hand skin temperature (T_{sk}). The value of T_{sk} decreased from a pre-immersion level of 30°C to a level slightly greater than the water temperature by 15 min. Next, the T_{sk} rested at approximately 8 to 9°C until 75 min. After immersion T_{sk} increased in a non-linear manner to a level of about 28°C by the end of the rewarming period at 135 min.

Fine Motor Tests

For the three fine motor tasks in Fig. 3.2 there were significant decrement in performance during cold-water immersion ($3.3 < F < 258.9$; $0.0001 < p < 0.001$). For the finger flexion and extension test (Fig. 3.2a) there was also a significant effect of gender (F=6.0, p=0.03) as evidenced by significantly longer flexion and extension ($p<0.05$) times for males than females at 75 min (p=0.04), and 90 min (p=0.01). Also during immersion at 45 and 105 min males showed a trend ($0.05 < p < 0.08$) for a longer flexion and extension time (Fig. 3.2A). The finger dexterity (Fig. 3.2B) and nut and bolt (Fig. 3.2C) tests showed no significant difference across gender

Gross Motor Tests

The peg and ring test had a significant decrease due to immersion in the cold water ($F=35.5$, $p<0.0001$) and no significant effect of gender ($F=2.2$, $p=0.17$). Despite this, at 90 min and 105 min, females performed the task significantly faster ($0.01< p <0.05$) than males and showed a trend to perform the task faster ($p=0.06$) at 120 min (Fig. 3.3). The time to complete the maze test was significantly increased by cold-water immersion ($F=2.7$, $p=0.01$) but there was no effect of gender (Fig. 3.4A). In the maze test a significant difference in errors rate (i.e. errors per second) was apparent across gender (Fig. 3.4B). Males made mistakes at significantly higher rates ($0.008 < p < 0.02$) than females at all points of comparison. The movement time test (Fig. 3.5A) showed a trend for females to have a slower time than the males ($F=3.3$, $p=0.10$). The reaction time to the light stimulus was not affected by water immersion ($F=0.17$, $p=0.99$) and there was no significant difference ($F=0.39$, $p =0.55$) across gender (Fig. 3.5B).

Grip Strength

Irrespective of gender, the absolute grip strength was significantly decreased ($F=71.6$, $p<0.0001$) after cold-water immersion (Fig. 3.6A). Except for 75 and 90 min, the males had significantly greater ($0.0001 < p < 0.01$) absolute grip strength than females ($F=84.9$, $p <0.0001$) at all points of the comparison. For grip strength values adjusted for the pre-immersion differences across gender, there was a significant effect of cold immersion ($F=56.7$, $p<0.0001$) that decreased grip strength but this adjustment removed the effect of gender ($F=0.17$, $p=0.99$) for grip strength (Fig. 3.6b). There was also a significant interaction of Time by Gender ($F=84.9$, $p<0.0001$) for absolute grip strength that appeared to be accounted for by male absolute grip strength decreasing and recovering more quickly than females. This interaction term was no longer evident when grip strength values adjusted for the pre-immersion differences across gender (Fig. 3.6B).

Comfort and Pain

Perceived comfort ($F=75.0$, $p<0.0001$) and perceived pain ($F=22.5$, $p<0.0001$) were significantly affected by cold immersion but gender showed no significant differences ($0.54 < F < 0.64$; $0.48 < p < 0.82$) during the experiment (Fig. 3.7A, B). During the first 15 min males and females comfort ratings decreased from approximately 1 to –6 to -7 (Fig. 3.7A) and pain ratings increased from an average of 1 to approximately 6 (Fig. 3.7B). After the 15 min point there was a moderate level of pain and discomfort until the end of immersion. After cold immersion the comfort and pain ratings approached pre-immersion values from 90 min onwards.

3.4 Discussion

Irrespective of gender, all fine motor task performances were significantly decreased due to cold immersion (Fig. 3.2). This follows from previous work that showed limb only cooling causes large decreases in fine motor task performance (3, 4). With respect to gender and fine motor tasks, only during the flexion and extension test were differences evident (Fig. 3.2A). The results suggest that the smaller females (Table 3.1), despite having similar levels of muscle and skin cooling (Fig. 3.1), performed equally or better on these fine motor tasks.

When larger upper limb muscle groups were employed for the gross motor tasks all performances for both gender were decreased by cold immersion with the exception of the reaction time test. These results follow from similar tests of gross motor tasks (3, 4) after upper limb cooling. When gender was considered, males did show some indications of poorer performance on the gross motor tasks. For 30 min following the cold immersion, males had some significantly longer completion times than females for the peg and ring test (Fig. 3.3). Also for the error rates in the maze test, males had a significantly higher rate throughout the entire experiment (Fig. 3.4B). This latter difference, however, appeared to be sustained from pre-immersion differences in error rates. On the contrary, for movement time (Fig. 3.5A), females showed a trend ($p=0.10$) for slower cold-induced movement times than males. For grip strength relative to pre-immersion values or grip strength adjusted for pre-immersion differences in gender, there were no differences between females and males (Fig. 3.6B). Overall the evidence did give some support that females performed better than males for the gross motor tasks in these experiments. This might suggest females could be better suited for manual work in cold environments.

As mentioned above, the reaction time test showed no effect of cooling or gender and these results help support that no core cooling was evident for these subjects. In our reaction test, the performance was dependent on a central processing of visual information that initiated a motor command to the external rotors of the upper arm. Reaction time and central processing time are known to increase with core cooling (16). Since performance on this reaction test was not different across the tests, this supports that no core cooling occurred. A sub group of subjects in this study (data not presented) were measured for tympanic temperature and this confirmed the results of Giesbrecht et al (5) that no core cooling occurred in our subject with only limb cooling.

Comfort and pain ratings showed no significant differences across gender and this suggested males and females have similar cold pain perception. Irrespective of gender during the first 15 min there were marked decreases in comfort ratings and increases in pain ratings relative to the pre-immersion. The results confirmed the view that the discomfort of cold immersion is the greatest during the initial minutes of limb cooling. This study extends this view to support that similar levels of discomfort are evident across gender with cold limb immersion.

Giesbrecht and Bristow (4) found in their study that total body cooling gave detrimental effects on performance of fine and gross motor tasks. Giesbrecht and colleagues in 1995 (6) went one step further to look at the relative importance of local cooling and whole body cooling on upper limb manual performance and strength. They found that regardless if body core is cool or warm, that there were similar decrements in upper limb manual performance and strength after cold-water immersion. They also found that fine motor tasks decreased by approximately 75% while gross motor tasks decreased by approximately 54%. Our findings were similar to Giesbrecht and colleagues (6) with fine motor tasks decreasing by approximately 71% and gross motor tasks (excluding grip strength) decreasing by 39% (Table 3.2).

With respect to pain and comfort ratings during cold immersion (Fig. 3.7A, B), our findings were supported by some studies and contradicted by other studies. Zeichner and colleagues (21) found that females had increased physiological arousal during a cold-pressor test, however, across gender their subjects rated the pain of cold immersion in a similar manner. Our results were also supported by the study of Lautenbacher and Rollman (11) who found that there was no significant difference across gender during a cold threshold test, nor in heat pain or warmth threshold tests. In contrast, studies by Keogh and Herdenfeldt (10) and by Hellstrom and Lundberg (9) showed that with cold pressor tests males had an increased threshold tolerance and decreased sense of pain compared to females. It does not appear that there is a consistent view in the literature with respect to gender differences in cold perception. Our subjects were not screened for pain tolerance. According to Hall and Davies (7) there is a significant difference in pain tolerance between athlete and non-athletes and this is a potential shortcoming of the current study and is a possible topic of further study.

Giesbrecht and colleagues (6) in a similar study suggested that fine motor tasks require superficial muscles in the forearm and fingers, that were immersed to a greater extent and cooled more than the more proximal upper limb and shoulder muscles used for gross motor tasks. This may explain why there were greater decreases in fine versus gross motor tasks after limb cooling (Table 3.2). Since un-perfused muscle is a better insulator than un-perfused skin (14, 18) and there is more muscle mass in the upper arm relative to the forearm and hand, this would allow for a slower decrease in tissue temperature and temperature in the upper limb. As a result it is suggested this is the reason for smaller decreases in gross motor tasks after limb cooling. Even so, it was surprising that our female subjects gave the same or better performance in fine motor tasks relative to males, since presumably our smaller females (Table 3.1) had relatively less skin and muscle insulation in their hands and forearms. Further studies are needed to examine differences in fine and gross motor tasks while differences in upper limb tissue masses are taken into account.

3.5 Conclusion

The results suggest that during and following limb upper cooling, females may show smaller decrements in some fine motor tasks and in gross motor tasks relative to males.

In addition males and females gave similar ratings of comfort and pain during and following these upper limb cold immersion tests.

3.6 References

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Table 3.1: Subject gender, height, weight, Body Mass Index (BMI) and age. Group values are the mean values ± Standard Error (SE).

Subject	Sex	Height (m)	Weight (kg)	BMI ($kg \cdot m^{-2}$)	Age (y)
1	M	1.74	64.7	21.4	22
2	M	1.75	77.8	25.4	21
3	M	1.81	89.5	27.3	25
4	M	1.73	73.7	24.6	42
5	M	1.76	78.0	25.2	26
6	M	1.78	88.2	27.8	22
7	F	1.47	45.0	20.8	25
8	F	1.61	57.0	22.0	21
9	F	1.70	52.5	18.2	45
10	F	1.64	63.6	23.6	21
11	F	1.66	77.3	28.1	21
12	F	1.57	60.4	24.5	21
Mean Male		1.76 ± 0.01	78.7 ± 3.8	25.3 ± 0.9	26.3 ± 3.2
Mean Female		1.61 ± 0.03	59.3 ± 4.5	22.9 ± 1.4	25.7 ± 3.1
Group Mean	-	1.69 ± 0.04	69.0 ± 5.7	24.1 ± 1.2	26 ± 3.4

Table 3.2: Percentage change in fine and gross motor tasks from pre-immersion values prior to cold limb immersion (n = 12, 6 males and 6 females).

Test Type	Test Name	Units	Pre-immersion (0 min)	End Immersion (75 min)	Percent change from pre-immersion level
Fine Motor Tasks	Flexion and Extension	(s)	1.71	12.90	-87%
	Finger Dexterity	(mm)	0.31	1.15	-73%
	Nut and Bolt	(s)	17.95	38.48	-53%
				mean	**-71%**
Gross Motor Tasks	Peg and Ring	(s)	12.99	27.96	-54%
	Maze Completion Time	(s)	27.03	29.89	-10%
	Maze Error Rate	(#/s)	0.38	0.65	-42%
	Movement Time	(ms)	26.62	49.38	-47%
				mean	**-39%**
Grip Strength	Relative Grip Strength	(%)	100	68.55	69
				mean	**-31%**

Figure 3.1: Mean bicep (A) and skin temperature (B) across gender prior to immersion at 0 min until 75 min of immersion and for 60 min of recovery (n = 12, 6 males and 6 females).

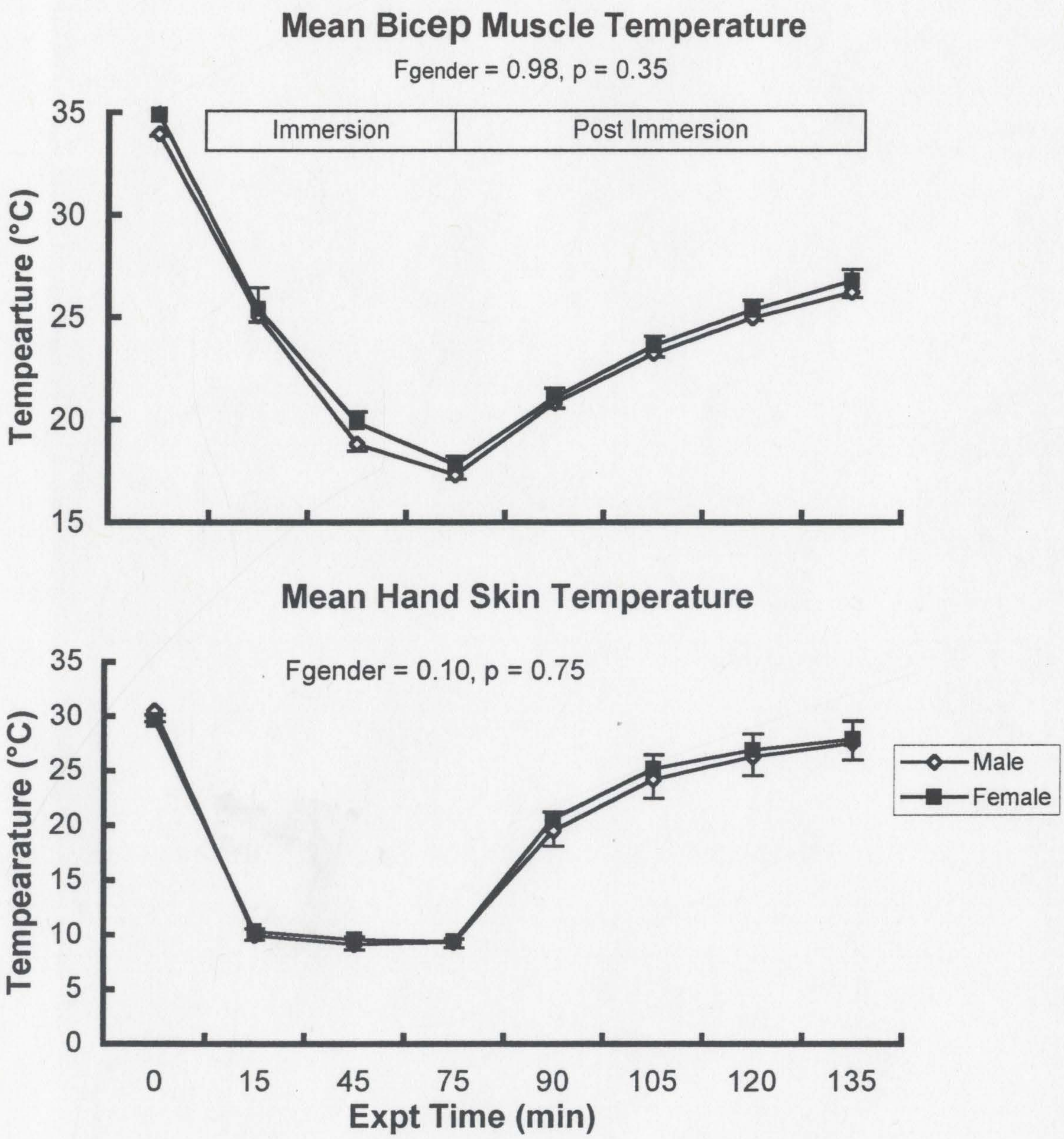


Figure 3.2: Fine motor task scores across gender prior to immersion at 0 min until 75 min of immersion and for 60 min of recovery A: Finger Extensions and Flexion, B: Finger Dexterity, C: Nut and Bolt Task (n = 12, 6 males and 6 females: *p <0.05).

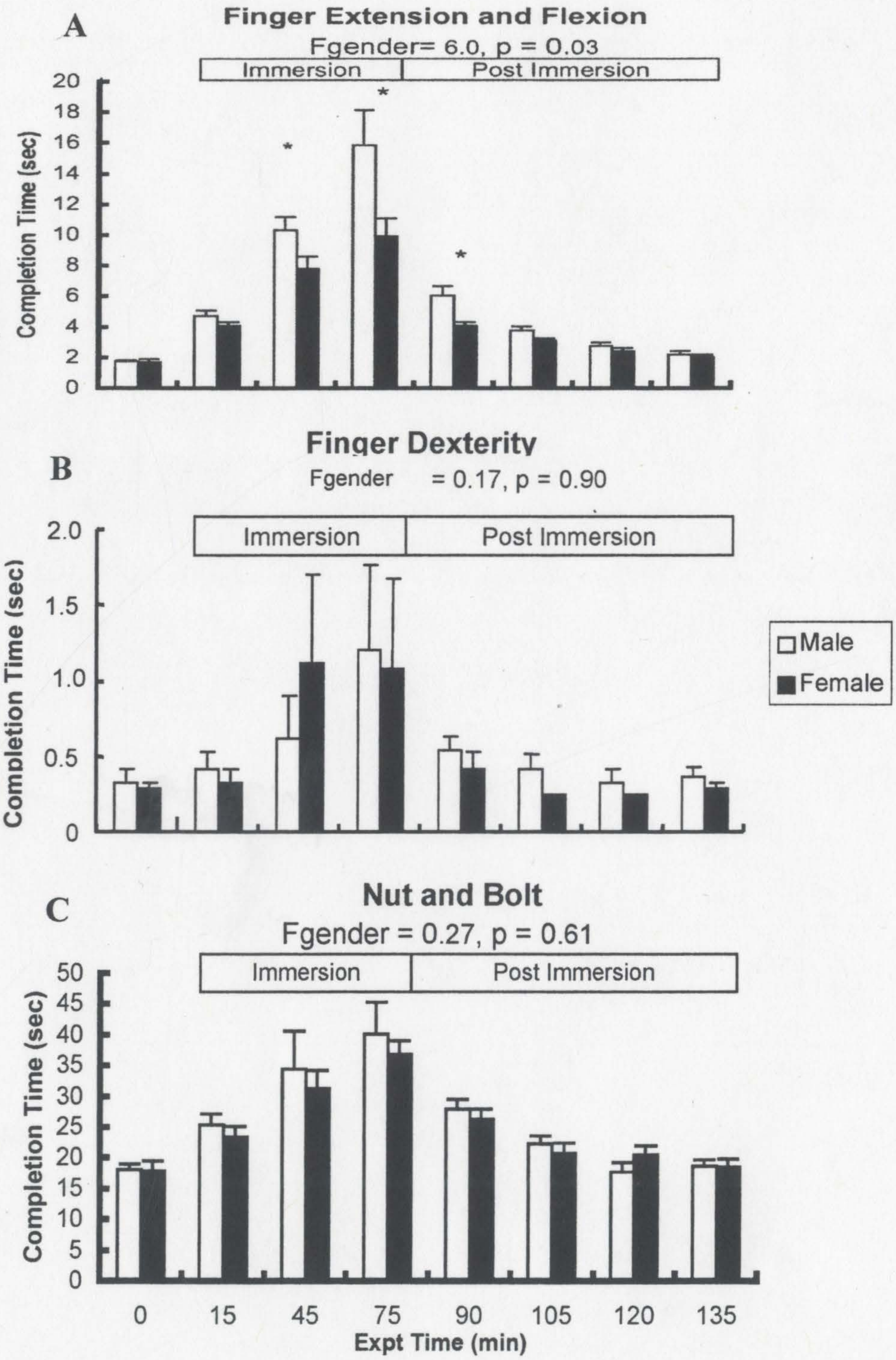


Figure 3.3: Peg and Ring scores across gender prior to immersion at 0 min until 75 min of immersion and 60 min of recovery (n = 12, 6 males and 6 females: *p <0.05).

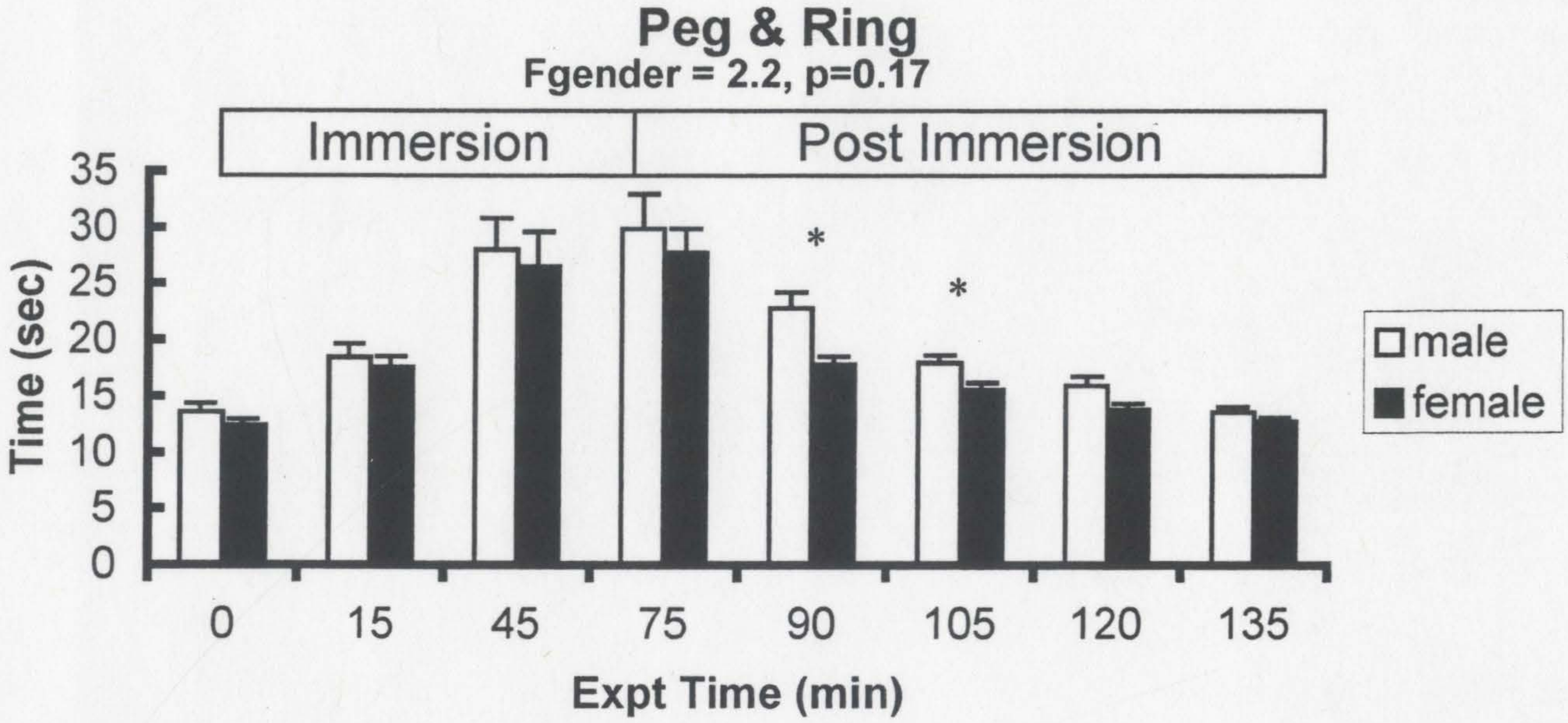


Figure 3.4: Maze completion times (A) and error rates (B) across gender prior to immersion, until 75 min of immersion and for 60 min of recovery after immersion (n = 12, 6 males and 6 females: *p <0.05, †p<0.01).

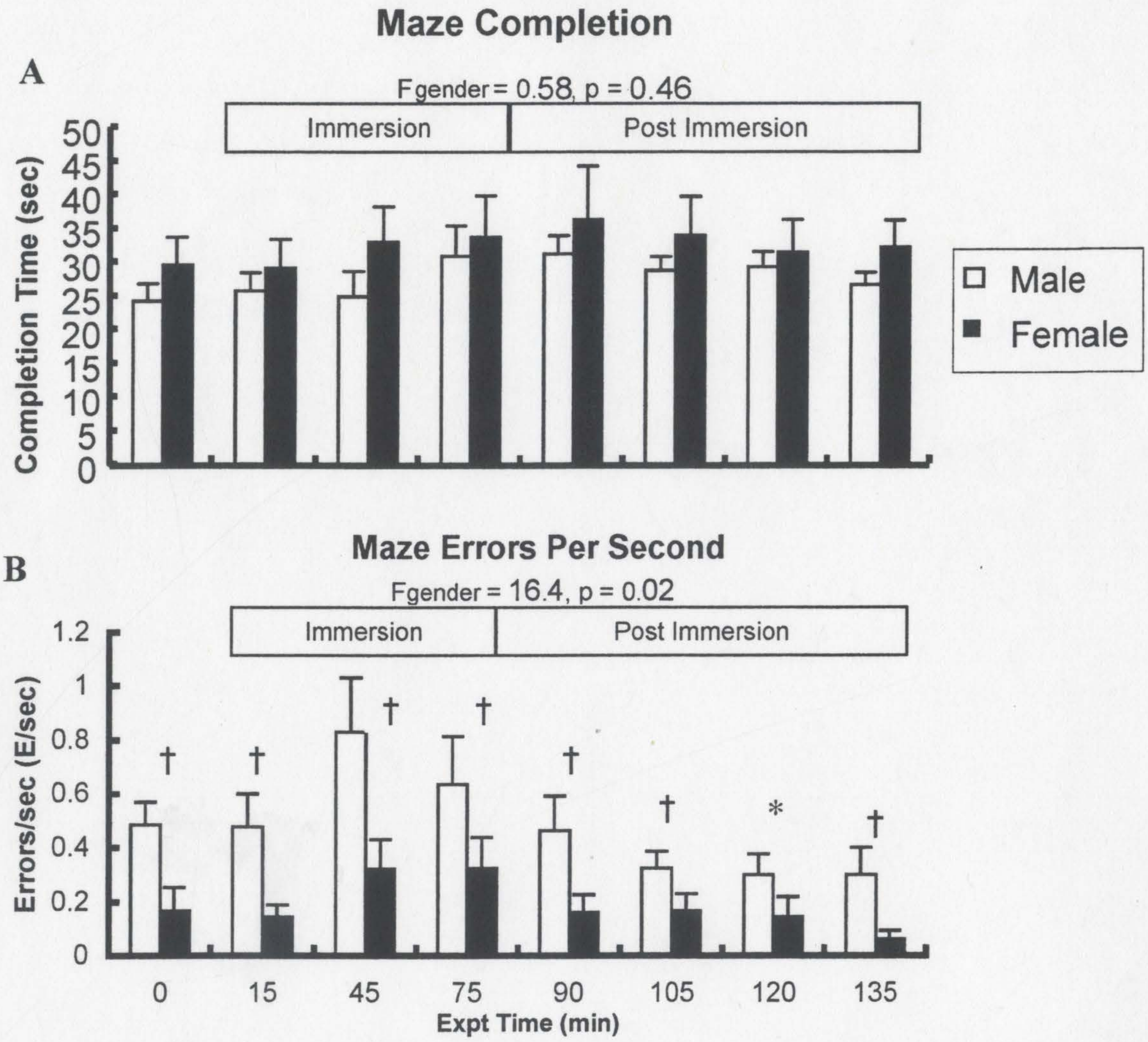


Figure 3.5: Movement (A) and Reaction (B) times across gender prior to immersion, until 75 min of immersion and for 60 min of recovery after immersion (n = 12, 6 males and 6 females; *p <0.05, †p<0.01).

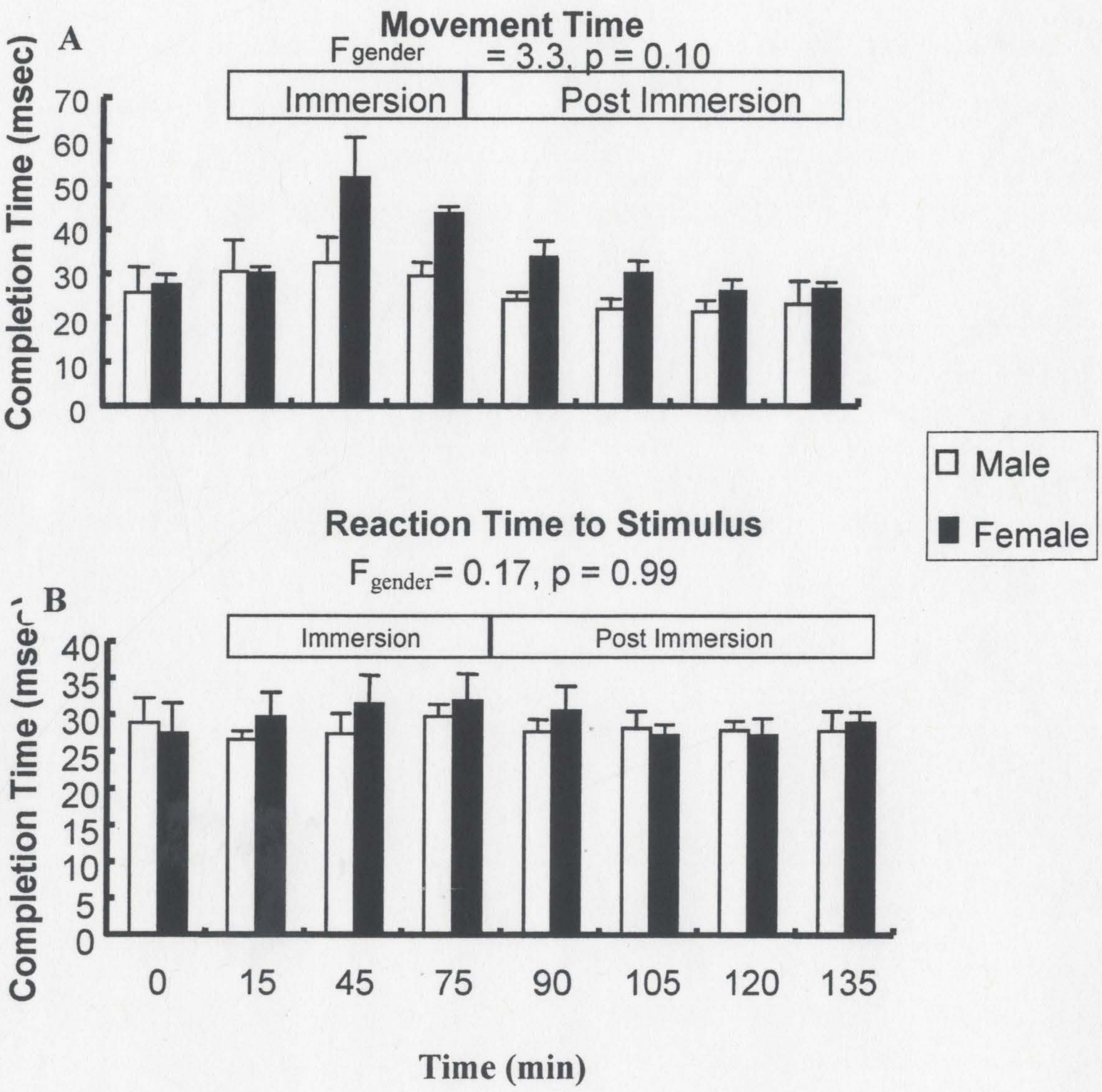


Figure 3.6: Absolute and relative grip strength scores across gender prior to immersion at 0 min until 75 min of immersion and 60 min recovery (n = 12, 6 males and 6 females: *p <0.05, †p<0.01).

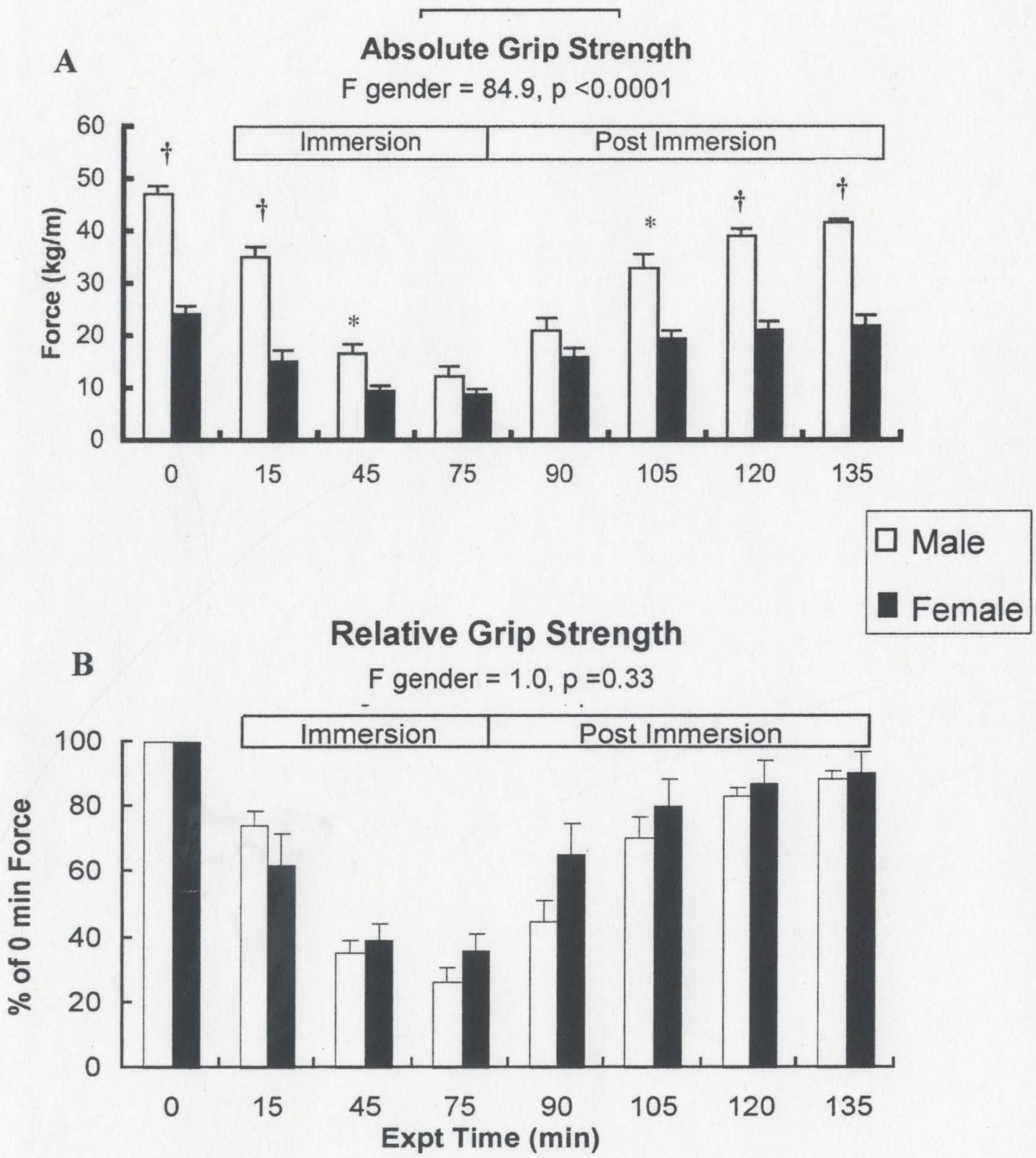
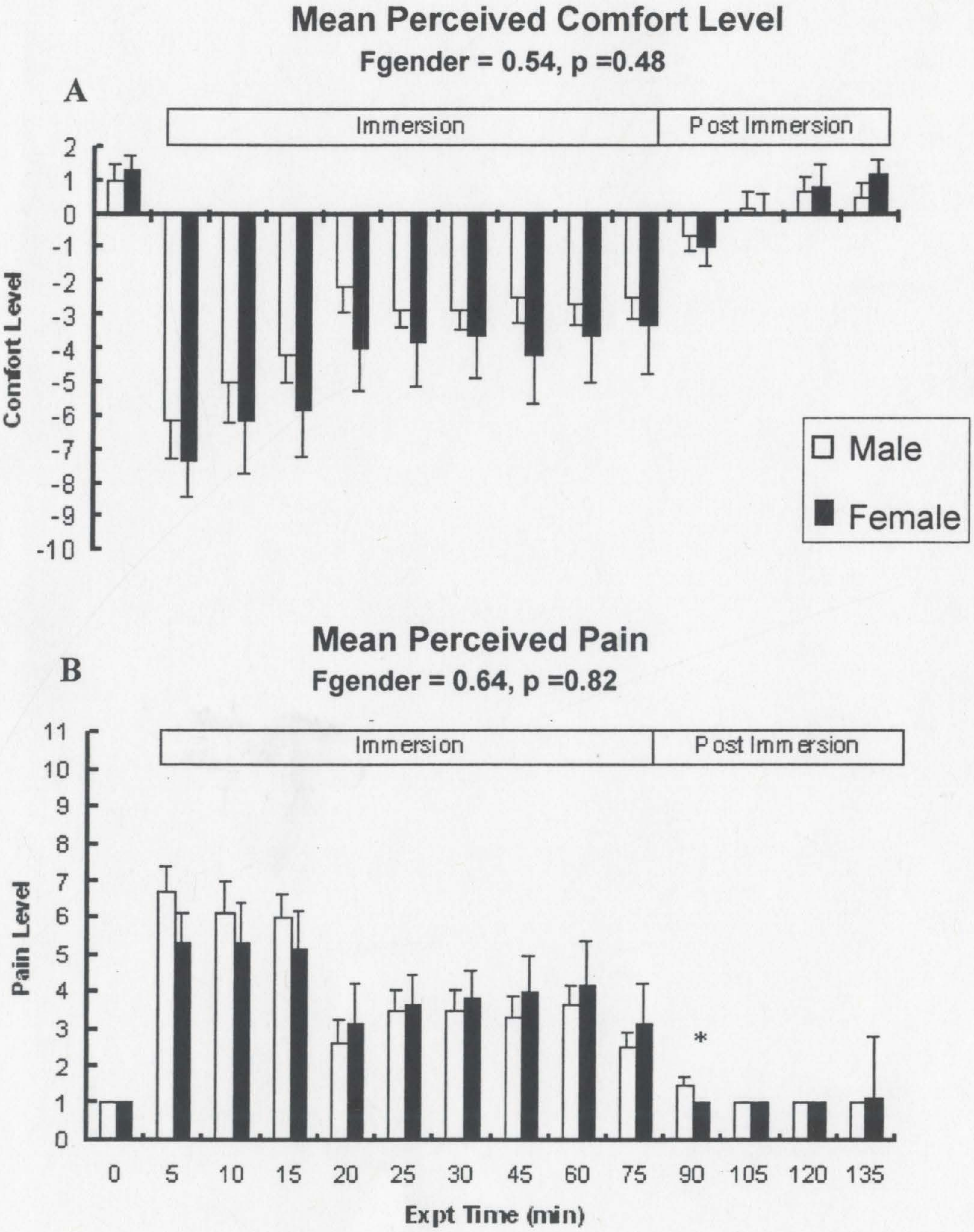


Figure 3.7: Mean comfort (A) and pain (B) levels across gender prior to immersion at 0 min until 75 min and 60 min of recovery following limb immersion. Perceived comfort scale: 2 = Comfortably Warm, -10 = Extremely Cold. Perceived pain scale: 1 = No Pain, 11 = Unbearably Painful (n = 12, 6 males and 6 females; *p <0.05).



Chapter 4: Limited Acclimation of the Upper Human Limb to Repeated Cold Water Immersion

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4.1 Abstract

This study investigated if the upper limb can be acclimated to cold by repetitively immersing the upper limb in cold water. On 5 consecutive days, 6 college-aged males of normal physique immersed their dominant upper limb for 75 min in an 8°C bath while intramuscular biceps brachii, and hand skin temperatures (T_{sk}) were monitored continuously. Prior to, during and for 60 min following the 5 daily immersions, fine and gross motor task performances were assessed together with ratings of pain and comfort. Immersion gave similar significant ($p<0.0001$) decreases in biceps brachii temperature from ~33.96 ± 0.10°C to ~16.48 ± 0.34°C on days 1 and 5. A significant Day by Time interaction for T_{sk} ($F=2.3$, $p=0.04$) was explained by significantly higher T_{sk} ($p=0.002$) prior to immersion and at different time points following immersion ($0.01< p < 0.02$) for Day 5 relative to Day 1. By Day 5 relative to Day 1 the finger flexion and extension times showed a trend for an improvement ($F=5.3$, $p=0.07$). The peg and ring test showed a trend for a significant Day by Time interaction ($F=2.15$, $p<0.06$) with the interaction explained by faster values on Day 5 versus Day 1 of acclimation. Relative grip strength showed a significant improvement ($F=21.0$, $p =0.006$) for Day 5 vs. Day 1. A significant improvement in comfort ($p<0.0001$) and pain levels ($p<0.0001$) were evident during the first 20 min of immersion on Day 5 relative to Day 1. In conclusion, a 5-day repeated cold immersion gave indications of the start of a cold-acclimation, as indicated by physiological and cold-perception changes plus improved manual performance.

Keywords: acclimation, cognition, cold, fine and gross motor tasks, manual dexterity

4.2 Introduction

Acclimation or acclimatization to cold can be for the whole body and/or locally for a limb or appendage. A study by Skreslet and Aarefijord (13) showed that there is a whole body acclimatization for scuba divers with multiple cold-water immersions. LeBlanc (9, 11, 12) looked at Inuit and Gaspé fishermen who live in cold environments and found that habituation occurred specifically for the extremities. Increased blood flow to the hands and better pain tolerance were reported (9, 11, 12). However, Inuit and Gaspé fishermen had similar response to controls in that they both shivered at the same level of core temperature (9, 11, 12). These populations are accustomed to having their extremities immersed in cold water, however, in response to the cold environments, they keep their body warm by wearing warm clothing. This study will focus on the latter, local acclimation, as evidenced in workers who expose just their upper limbs to cold environments.

Studies on acclimation to cold water immersion with respect to cold induced pain (1, 3, 8, 9, 11, 12) have shown that cultures exposed to cold water through out their lives show decreases in perceived pain when compared to others from warmer climates. The nature of short-term acclimation to pain from cold immersion does not appear to have addressed in the literature. As such, the following investigation was conducted to examine the nature of short-term cold acclimation of the limb in male humans.

The specific questions addressed in this study were: Is there a cold acclimation after 5 consecutive days of upper limb cold immersion as assessed by skin temperature changes and by performance on both tests of fine and gross motor tasks and grip strength? Secondly, is there an acclimation of perceived comfort and pain after 5 consecutive days of upper limb cold immersion?

4.3 Methodology

4.3.1 Subjects

Six males of normal physique and college age participated in the study after having read and signed an informed consent form. The sample size was determined using a power calculation. The difference worth detecting was set at 5% with an alpha level of 0.05 and with a beta value of 0.8 and a standard deviation of 10% of the projected means (5). The study was conducted with approval from the human ethics boards or committees at the appropriate universities. The subjects were instructed to abstain from alcohol, caffeine, or medication for a period of 24 hours before participation. Their dress consisted of shorts and T-shirt.

4.3.2 Instrumentation

An 18 mm, 22-gauge thermocouple (Mon-a-therm Myocardial, Mallinckrodt Med Inc., St. Louis, MO, USA) was used in the lateral bicep of the dominant arm. Copper-constantan thermocouples were taped on the dorsal surface of the hand of the dominant arm as an index of skin temperature (T_{sk}). These probes were secured to the skin with Elastoplast* waterproof tape (Smith + Nephew). The temperatures were collected by a national Instruments Data Acquisition System (National Instr., Austin, TX, USA controlled by LabVIEW software(version 5.1, National Instr., Austin, TX, USA).

Manual Dexterity and Strength Tests

A series of 7 tests were constructed to measure fine and gross motor performance of the dominant arm. Prior to the actual experiment training, on the performance tests was conducted over 5 trials or until a plateau in performance was evident. One group of tests took 3 to 4 min to complete. The tests and the order they were preformed are as follows:

Finger flexion and extension: Subjects closed and opened their dominant hand as rapidly as possible (dynamic movement) five times with their hand held at arm's length. Time was recorded at the commencement of the exercise by the experimenter and ended when the subject completed the final extension.

Grip Strength (modified from Canadian Physical Fitness and Lifestyle Appraisal (CPFLA) protocol for Grip Strength): A hand dynamometer (Takei Instruments Co., Japan, Grip D [Digital Hand Grip Meter]) was placed in the hand with the grip of the dynamometer placed so the second joint of the index finger fits snugly under the hand and takes the weight of the instrument. It was held in line with the forearm at thigh level away from the body. The seated subject then squeezed vigorously, exerting maximum force (kg: 0 to 100 kg ±2.0 kg, measured to 0.1 kg), and exhaled.

Finger Dexterity Test: Subjects, while seated, attempted to pick up the smallest disc possible out of six discs starting with the smallest disc. The measurement of the disc was then recorded. The six discs had a diameter of 2.5 cm and ranged in length from 0.25 to 4 mm. The test was similar to that in (5).

Peg and Ring Test: Six pegs (2 cm in diameter, and 4 cm in length) were fixed on to a board (30.5 cm by 30.5 cm) arranged in two rows of three from top to bottom. The pegs in each row were spaced 5 cm, and the rows were spaced by 10 cm. A larger peg (2 cm in diameter, and 9 cm in length) was place at the top of the board for starting placement of the rings (4 cm outside diameter, 2.5 cm inside diameter). The subjects were seated, and commenced at the signal of an experimenter. The time taken to place one ring on each peg (one at a time) and then replace them (one at a time) back to the start peg was recorded. The test was similar to that in (5).

Nut and Bolt Test: A board (45 cm by 45 cm) having four bolts fixed to it (7mm diameter, 18mm in length). At the top of the board was a container holding the four nuts (12mm outside diameter, 6mm inside diameter, 6mm high) to be fitted on to the bolt. Bolts were arranged in a square (8 cm sides). The subjects were seated, and commenced at the signal from an experimenter. The time to fit all four nuts on the bolts was recorded. The test was similar to that in (5).

Maze Test: The subjects were instructed to navigate through a maze with the probe as fast as possible and with the least number of "hits" (hitting the probe off the side of the maze; counted via a counter and emitted a beep) as possible. At the signal of the experimenter the subjects commenced and the time taken to navigate to the end, and the number of "hits" were recorded. The test was similar to that in (5).

Movement and Reaction Time: Reaction time is measured via a Multi-choice Reaction Timer (Lafayette Instrument Co.) and movement time is measured via a Stop Clock (Lafayette Instrument Co.). Subjects were seated and placed their fingers on the start button. When the stimulus light (Lafayette Instrument Co.) turned on the subject move their fingers from the start to finish button (buttons 60 cm apart and each encased in in a waterproof 10 cm^3 plexiglass cube). Movement time was recorded as time from the Stop Clock minus time from Multi-Choice Reaction Timer, and reaction time was recorded from the Multi-Choice Reaction Timer. The test was similar to that in (5).

Arm Cooling Tank

Subjects sat in a height adjustable chair so as to allow the subject a comfortable height to immerse their dominant arm to the level of the axilla. The arm tank was constructed of PVC tubing 95 cm in depth and 22 cm in diameter, insulated with ARMORFLEX. An Endocal Refrigerated Circulating Bath (NESLAB, Portsmouth, NH) was used to cool the water entering the tank. The inflow tube from the bath to the tank diverged into two insulated (ARMORFLEX) tubes (84 cm in length) connecting and depositing the chilled water into the top of the tank via 12, 1 cm holes located 13 cm down from the top about the circumference. An outflow tube was located at the bottom of the tank and connected to the bath via another tube. The temperature of the water in the arm tank was observed via LabVIEW (National Instruments, Austin, TX) and a thermometer (Brannan, England) monitored the water temperature of the NESLAB bath. Maintenance of temperature was done via the NESLAB's bath's temperature dial (min - 30°C and max 100°C) and addition of ice to the arm tank. Flow from the bath to the arm tank was controlled via a dial on the bath; the water level could not exceed a set level in the bath because of the risk of overflowing the bath, which limited the flow rate of the bath. The water temperature for this experiment was set to 8ºC.

4.3.3 Protocol

A medical doctor used a local anesthetic (2% lidocaine) to a muscle temperature thermocouple (T_{mus}). This site was chosen since it represents a considerable muscle mass of the arm well distant from major vessels or nerves as stated by Giesbrecht and colleagues (5).

The subject's dominant arm was immersed for 5 successive days. After thermocouples were positioned in and on the subject's dominant arm, the first series of tests were performed prior to arm immersion. On Day 1 and 5, the subject immersed his dominant arm in 8°C water for 75 min followed by 1 hour of recovery. For days 2 to 4 subjects immersed their arm for 75 min but were not monitored through the 1 hour of recovery.

Tests of manual dexterity and strength were completed at 15, 45, and 75 min from beginning of immersion. At the beginning of each trial the subject would remove their arm from the tank and then place their dominant hand in the starting position on a table next to them with all test materials. After completion of the trial, the subject's dominant arm was re-immersed. For Day 1 and 5, following 75 min, subjects had a passive re-warming in the ambient air for 60 minutes with 4 test trials at 90, 105, 120, and 135 min after the start of immersion.

The time of day each subject took part was kept at similar times for each trial during pre-immersion orientation trials. Though according to Castellani and colleagues (2), vasoconstriction are not affected by the time of day.

Pain and Comfort Ratings

A subjective rating of pain and comfort was made employing the scales developed by Havenith and colleagues (7). The scale for comfort was from +2 (Comfortably Warm) to -10 (Extremely Cold). For pain the scale employed was from +1 (No Pain) to +11 (Unbearably Painful).

4.3.4 Statistical Analysis

To establish the effects of repetitive cooling on test performance, a two-way univariate ANOVA was employed with repeated factors of Time (0, 15, 45, 75, 90, 105, 120 and 135) and Day (Day 1 and Day 5). Dependent variables included the performance scores on the 7 tests mentioned above. A similar two-way ANOVA was employed for comfort and pain ratings during cold limb immersion. In the comfort and pain ANOVA to account for the rapid changes the factor TIME included more levels (0, 5, 10, 15, 20, 25, 30, 45, 75, 90, 105, 120, and 135 min) in the first 30 minutes of immersion. The level of significance for these analyses was set at 0.05. Means comparisons were made between mean Day 1 and Day 5 values at each level of time with *a priori* orthogonal contrasts. Results were considered significant a level of 0.05.

4.4 Results

Muscle Temperature (T_{mus}) and Hand Skin Temperature (T_{sk})

From pre immersion until the end of immersion at 75 minutes, T_{mus} significantly dropped by approximately 50% and no significant differences (F_{day}= 1.20, p =0.32) were seen between Day 1 at the start of acclimation and Day 5 at the end of the acclimation period (Fig. 4.1A). After immersion T_{mus} increased in a non-linear manner to a level of about 25°C at the end of the rewarming period at 135 min.

The value of T_{sk} decreased from a pre-immersion level of ~31°C to a level slightly greater than the water temperature by 15 min. Next, the T_{sk} remained at approximately 9 to 10°C until 75 min. After immersion T_{sk} increased in a non-linear manner to a level of about 28°C by the end of the rewarming period at 135 min. Although for hand skin temperature (T_{sk}) there was no effect of Day (F=1.15, p =0.33) after 5 days of immersions, T_{sk} was higher (p=0.002) prior to immersion at 0 min and following immersion at 120 min (p=0.01) and 135 min (p=0.02) in the rewarming period (Fig. 4.1B). This was also evident from the Day by Time interaction that was significant for hand skin temperature (F=2.3, p=0.04).

Fine Motor Tests

Irrespective of the day of immersion, for the three fine motor tasks in Fig. 4.2, there were significant decrements in performance due to the cold-water immersion

(0.0001< p <0.05). For the finger flexion and extension test (Fig. 4.2A) there was an overall trend for a main effect of Day (F=5.3, p=0.07) as evidenced by significantly faster flexion and extension times on Day 5 versus Day 1 at both 45 min (p=0.006) and at 75 min (p=0.003) of cold water immersion. For the finger dexterity test (Fig. 4.2B) there was no overall effect of Day (Fig. 4.2B), although after 15 min of immersion there was a lower dexterity score on Day 5 than on Day 1. The nut and bolt test showed no significant effect of Day during the acclimation period, although at 45 min the completion time of the task was significantly faster on Day 5 relative to Day 1 (Fig.4.2C).

Gross Motor Tests

The peg and ring test had a significant decrease in performance due to immersion in the cold water (F=30.6, p<0.0001) and no significant effect of Day (F=0.67, p=0.45). There was also a trend (F=2.15, p=0.06) for a Day by Time interaction for the peg and ring test that was explained by significantly faster completion time during immersion and at 45 min (p =0.002) on Day 5 relative to that on Day 1 (Fig. 4.3).

The time to complete the maze test was significantly increased by cold-water immersion (F=2.7, p=0.02) but there was no effect (F=1.59, p=0.26) of the 5 day acclimation (Fig. 4.4A). For the maze test, irrespective of the Day, an effect of cooling (F=8.97, p=0.0001) was evident for error rate (i.e. errors per second) (Fig. 4.4B) but no effect of the acclimation period was evident (F=0.12, p=0.75). except at 45 min.

The movement time test (Fig. 4.5A) showed a significant effect of cold immersion on performance ($F=4.2$, $p=0.002$) but no effect of Day ($F=1.5$, $p=0.28$). The reaction time to the light stimulus was not affected by water immersion ($F=0.65$, $p=0.70$) and there was no significant difference ($F=0.03$, $p=0.86$) across 5 days of acclimation to cold (Fig. 4.5B).

Grip Strength

Irrespective of the day of limb immersion, the absolute grip strength was significantly decreased ($F=77.9$, $p=0.0001$) due to cold-water immersion (Fig. 4.6A). The acclimation period had no significant effect over the 5 days of immersion ($F=0.00008$, $p=0.99$). For grip strength values relative to the pre-immersion differences across between Day 1 and Day 5, there was a significant effect of cold immersion ($F=86.2$, $p<0.0001$). As well the 5 days of acclimation significantly (Fig. 4.6B) influenced relative grip strength ($F=21.0$, $p=0.006$). The relative grip strength was significantly greater on Day 5 than on Day 1 during immersion at 15 min ($p=0.0007$) and at 45 min ($p=0.006$) and during rewarming at 105 min ($p=0.0006$), and at 135 min ($p=0.009$) (Fig. 4.6B). There was also a trend for larger relative grip strength at 120 min ($p=0.05$). There was a significant interaction of time by Day ($F=2.9$, $p=0.02$) for relative grip strength that appeared to be accounted for by Day 5 relative grip strength decreasing more slowly during immersion and increasing more slower during the rewarming period (Fig. 4.6B).

Comfort and Pain

Perceived comfort (F=22.3, p<0.0001) and perceived pain (F=16.8, p <0.0001) were significantly affected by cold immersion irrespective of the day of immersion. Although no significant difference for the main effect of Day were evident (Fig. 4.7A, B), in the first 15 min for pain and during the first 20 min for comfort the ratings were significantly improved by Day 5 of immersion (Fig 4.7A, B). After the 15 min point there was a moderate level of pain and discomfort until the end of immersion. After cold immersion the comfort and pain ratings approached pre-immersion values from 90 min until 135 min.

4.5 Discussion

The main finding in this study was that despite repetitive immersion of the limb in cold water for 5 consecutive days, there was only a limited acclimation of fine motor tasks and upper limb strength. It was striking to note that the hand skin temperature prior to immersion and in the later stages of rewarming following immersion was significantly higher on Day 5 relative to Day 1. This suggests the first stages of local cold adaptation or acclimation were evident, since a higher skin temperature would indicate a greater surface skin blood flow. Brown and colleagues (1), Egan and colleagues (3), and Leblanc (9-12) have shown that an increased skin blood flow is an indication of a cold acclimatization. It would follow that the fine motor tasks that began to show some improvements by Day 5 (Fig. 4.2) and subjects were able to benefit from the increased peripheral blood flow (Fig. 3.1B).

To the best of our knowledge this is the first study to indicate that the comfort and pain ratings significantly improved in the first 15 to 20 minutes of limb immersion after 5 days of repeated cold-water immersion. This may have practical benefits since in the first few min after an open water cold immersion, life saving tasks are needed by the immersed individuals. A cold acclimated individual that can better tolerate the pain of cold-water immersion would be in a better position to perform life saving tasks.

The T_{mus} followed very much the same pattern during cold water immersion as that of T_{mus} in Giesbrecht and colleagues (5) study. Our study extends these previous findings to address the cold acclimation and the re-warming of the limb after the cold immersion. It is of note that the fine and gross motor task performance was still decreased after 60 minutes of rewarming in room air at ~ 22°C. This appears to be a function of the continued depression of T_{mus} since by 60 min post immersion T_{sk} had reached close to the pre-immersion levels.

Giesbrecht and Bristrow (4) found that cooling of the entire body had detrimental effects on performance of fine and gross motor tasks. It was not clear if these affects were due to core or limb cooling. Subsequently core temperature was shown by Giesbrecht and colleagues (5) to not change during the same limb-only immersion protocol as employed presently. They reported that regardless if there is a cool or warm body core, the majority of the detrimental effects of cold-water immersion on manual performance and strength are dependent on the temperature of the limb. Our study lends further support to the view that the decreases in manual performance with limb cooling arise from a local tissue cooling and not a central core cooling. They also found that fine motor tasks were more affected detrimentally than gross motor tasks; 75% compared to 54% respectively. Our findings were similar to Giesbrecht and colleagues (5) and the results are summarized in Table 4.2.

Our findings agree with the literature on perceived pain and acclimatization/acclimation to local cooling of the hands and/or fingers to cold water. According to numerous studies (1, 3, 9, 11, 12), acclimation/acclimatization to local cooling of the hands and/or fingers results in an increase in blood flow and a decrease in the sensation of pain. Though this study did not study cutaneous blood flow, we did see some indications of higher hand skin temperature on Day 5. This would indicate a higher skin blood flow in the subjects after 5 days of cold-water immersion.

A significant decrease in pain sensitivity was observed at the initial stages of immersion after which the pain levels for both days stayed the same for the remainder of the experiment (rest of immersion and the re-warming period). During the rest of the experiment Day 5 perceived pain was not different than that on Day 1. Subjects were not screened for suffering of pain. According to Hall and Davies (6) and Sternberg and colleagues (14) there is a significant difference in pain tolerance between athlete and non-athletes. As well, it could be postulated that offshore workers with their hands constantly being exposed to cold air and more specifically water may have a higher pain tolerance than the general public. A potential further study to extend the understanding on cold perception will be to screen subjects for pain tolerance while employing similar protocol as reported herein.

4.6 Conclusion

The results show limited evidence of cold local acclimation for fine motor tasks and grip strength, but not for gross motor tasks. Perceived pain and comfort showed limited but significant improvements during the first 15 to 20 min of cold immersion.

4.7 References

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Table 4.1: Subject mean age, height, weight, and body mass index (BMI). Values are the mean ± standard error (SE).

Subject	Age (y)	Height (m)	Weight (kg)	BMI (kg • m^{-2})
1	22	1.74	64.7	21.4
2	21	1.75	77.8	25.4
3	25	1.81	89.5	27.3
4	42	1.73	73.7	24.6
5	26	1.76	78.0	25.2
6	22	1.78	88.2	27.8
Mean	26.3	1.76	78.7	25.3
SE	(3.81)	(0.01)	(3.78)	(0.94)

Table 4.2: The percentage change in fine and gross motor tasks from 100% values prior to cold limb immersion (n=6).

Test Type	**Test Name**	**Units**	**Pre-immersion (0 min)**	**End Immersion (75 min)**	**Percent change from pre-immersion level**
Fine Motor Tasks	Flexion and Extension	(s)	1.77	14.32	-88%
	Finger Dexterity	(mm)	0.46	1.21	-62%
	Nut and Bolt	(s)	16.80	39.19	-57%
				mean	**-69%**
Gross Motor Tasks	Peg and Ring	(s)	13.84	28.66	-52%
	Maze Completion Time	(s)	24.64	29.54	-17%
	Maze Error Rate	(#/s)	0.42	0.64	-35%
	Movement Time	(ms)	23.50	29.92	-21%
				mean	**-32%**
Grip Strength	Relative Grip Strength	(%)	100	75.36	**-25%**

Figure 4.1: Mean bicep brachii (A) and hand skin temperature (B) on days 1 and 5 prior to immersion at 0 min until 75 min of immersion and for 60 min of recovery in room air (n = 6 males *p <0.05).

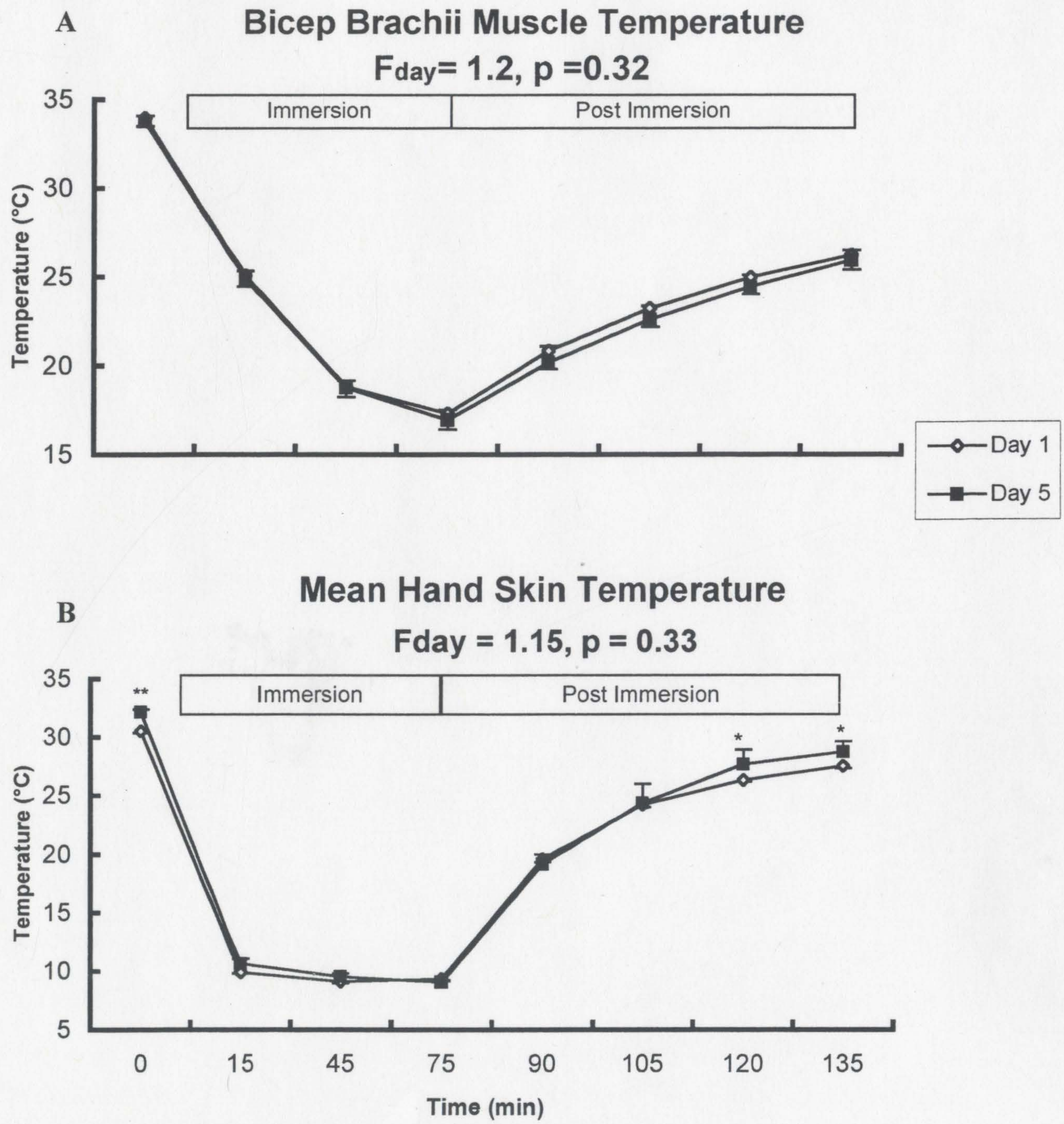


Figure 4.2: Fine motor task performance across days 1 and 5 prior to immersion at 0 min, until 75 min of immersion and for 60 min of recovery following limb immersion in room air. Values are mean ± standard error (n= 6 males, ** $p < 0.01$, *** $p<0.001$). A: Finger Extensions and Flexion, B: Finger Dexterity, C: Nut and Bolt Task

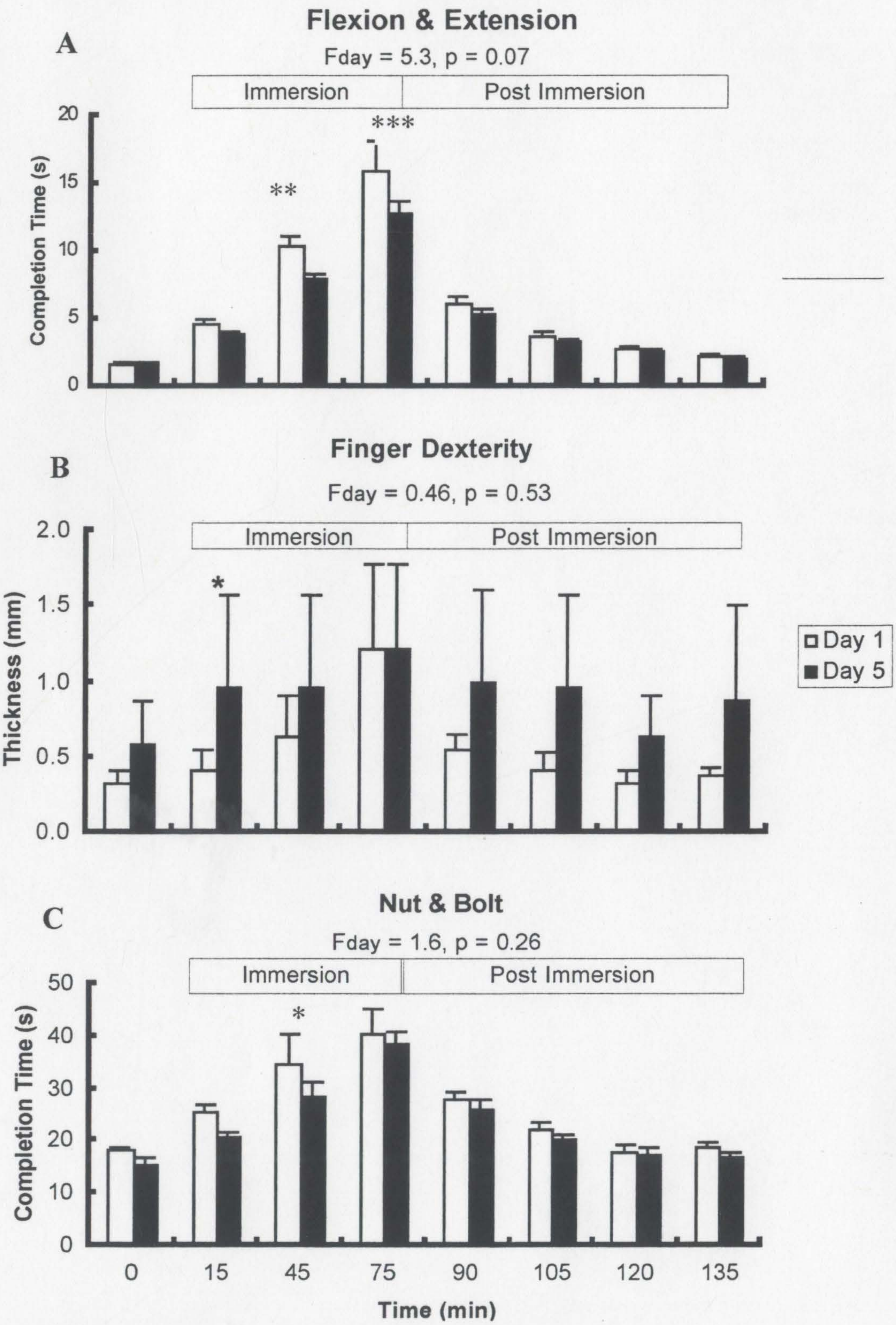


Figure 4.3: Peg and ring task completion time across days 1 and 5 prior to immersion at 0 min, until 75 min of immersion and for 60 min of recovery following limb immersion in room air. Values are mean ± standard error (n= 6 males, *** $p<0.001$).

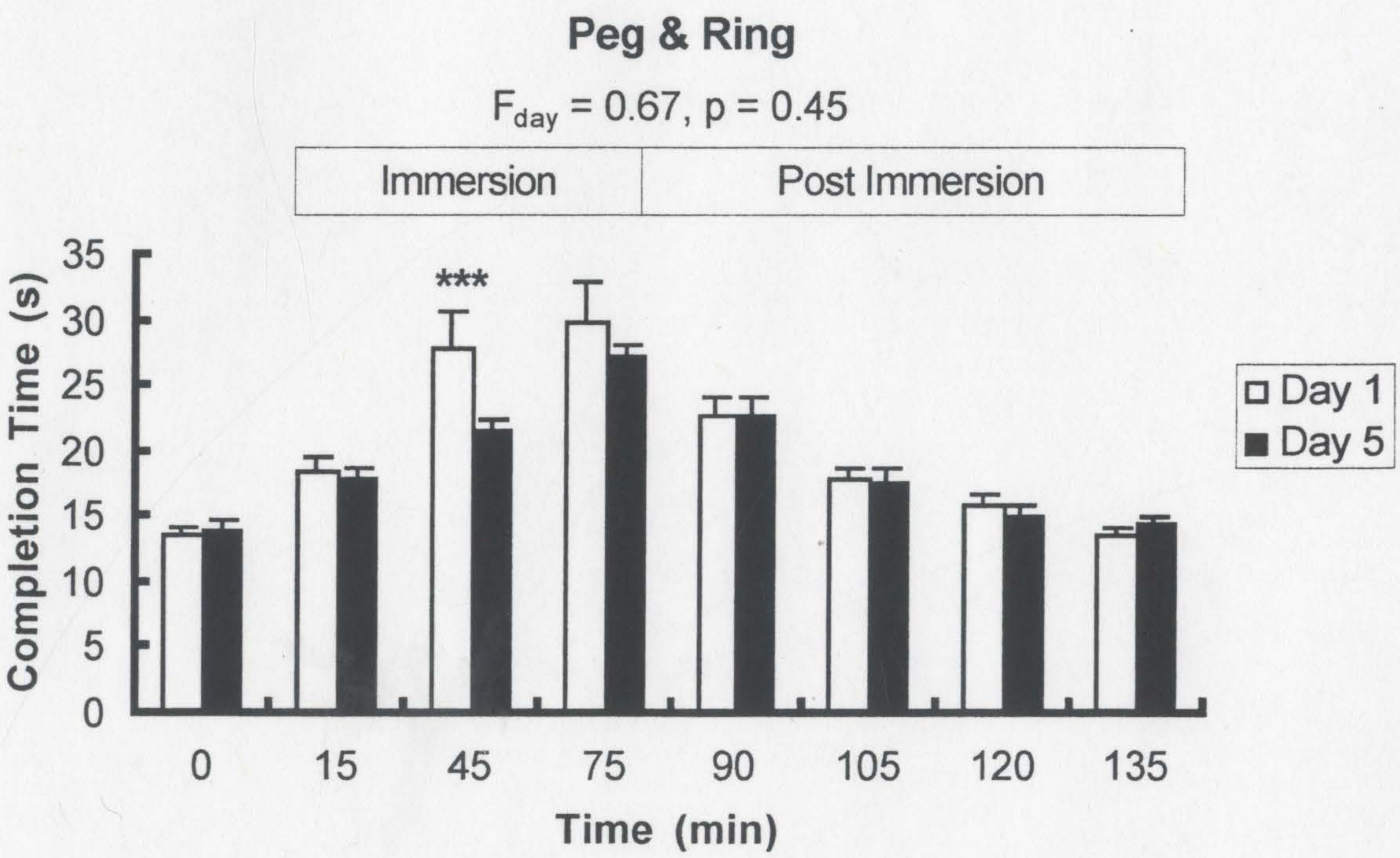


Figure 4.4: Maze completion time (A) and error rate (B) on days 1 and 5 prior to immersion at 0 min, until 75 min of immersion and for 60 min of recovery following limb immersion in room air. Values are mean ± standard error (n= 6 males, * $p < 0.05$, ** $p < 0.01$).

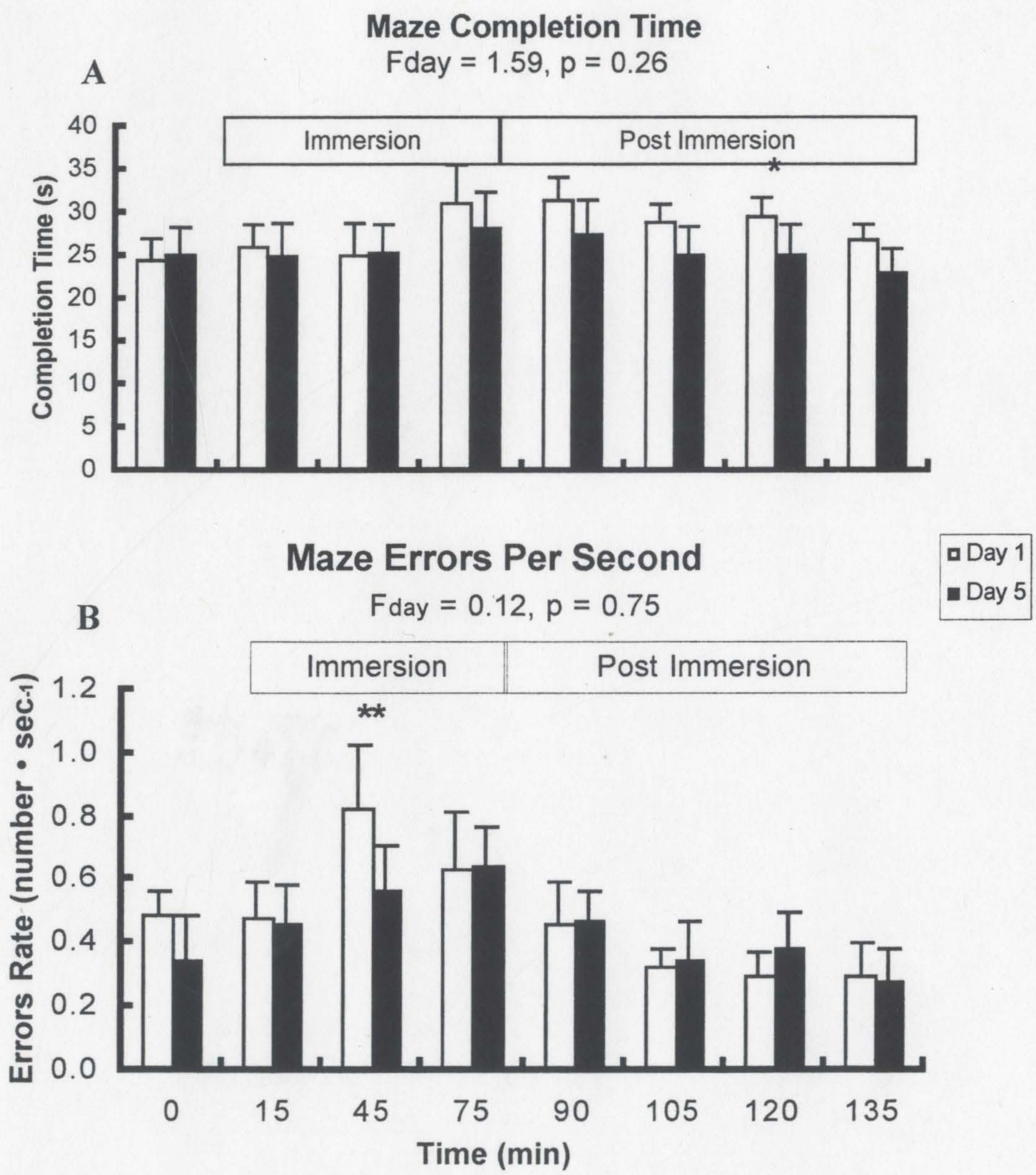


Figure 4.5: Movement (A) and reaction (B) times across days 1 and 5 prior to immersion at 0 min, until 75 min and 60 min of recovery following limb immersion in room air (n= 6 males).

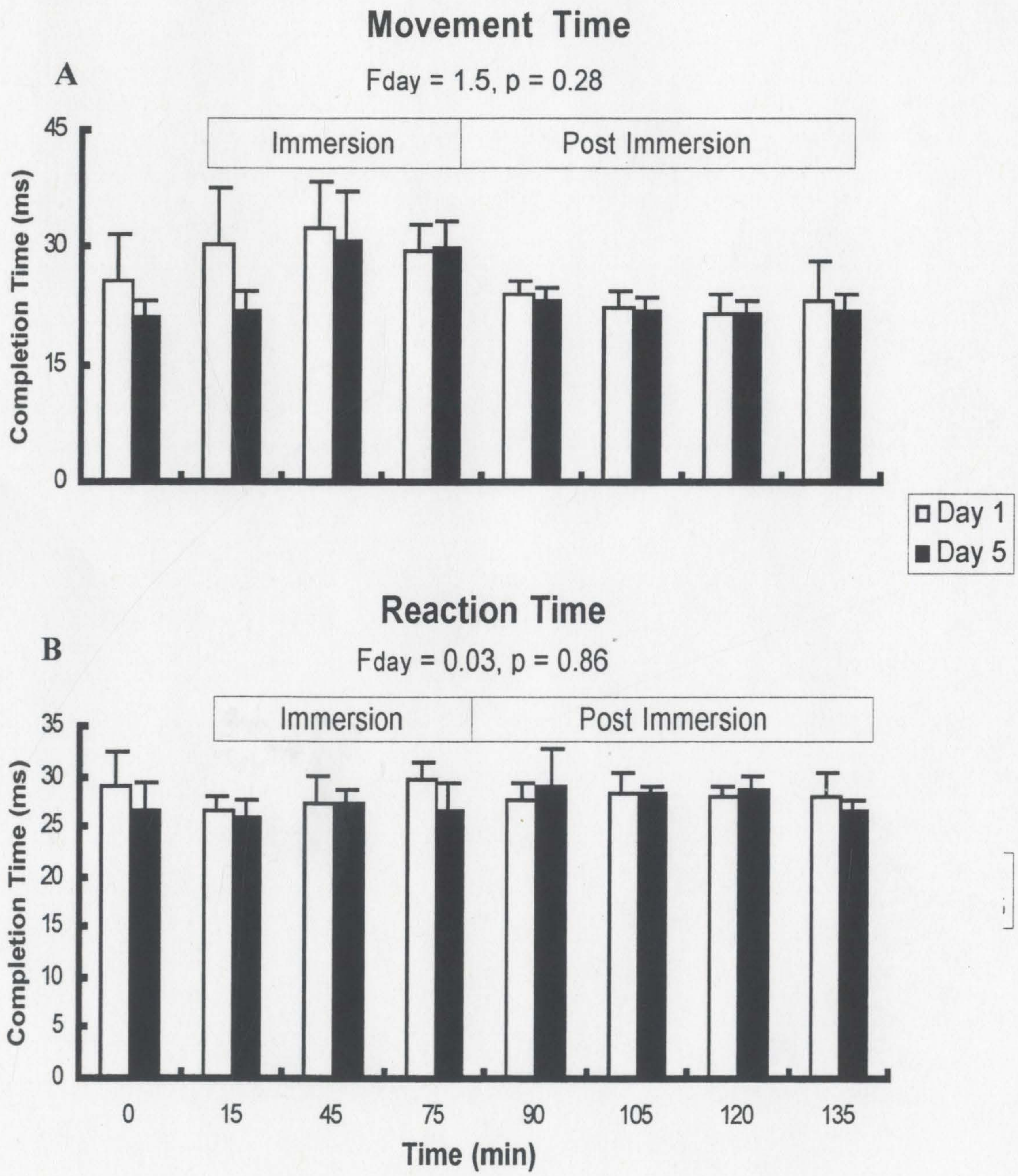


Figure 4.6: Absolute and relative grip strength scores across days 1 and 5 prior to immersion at 0 min, until 75 min of immersion and 60 min of recovery following limb immersion in room air. Values are mean ± standard error (n= 6 males, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

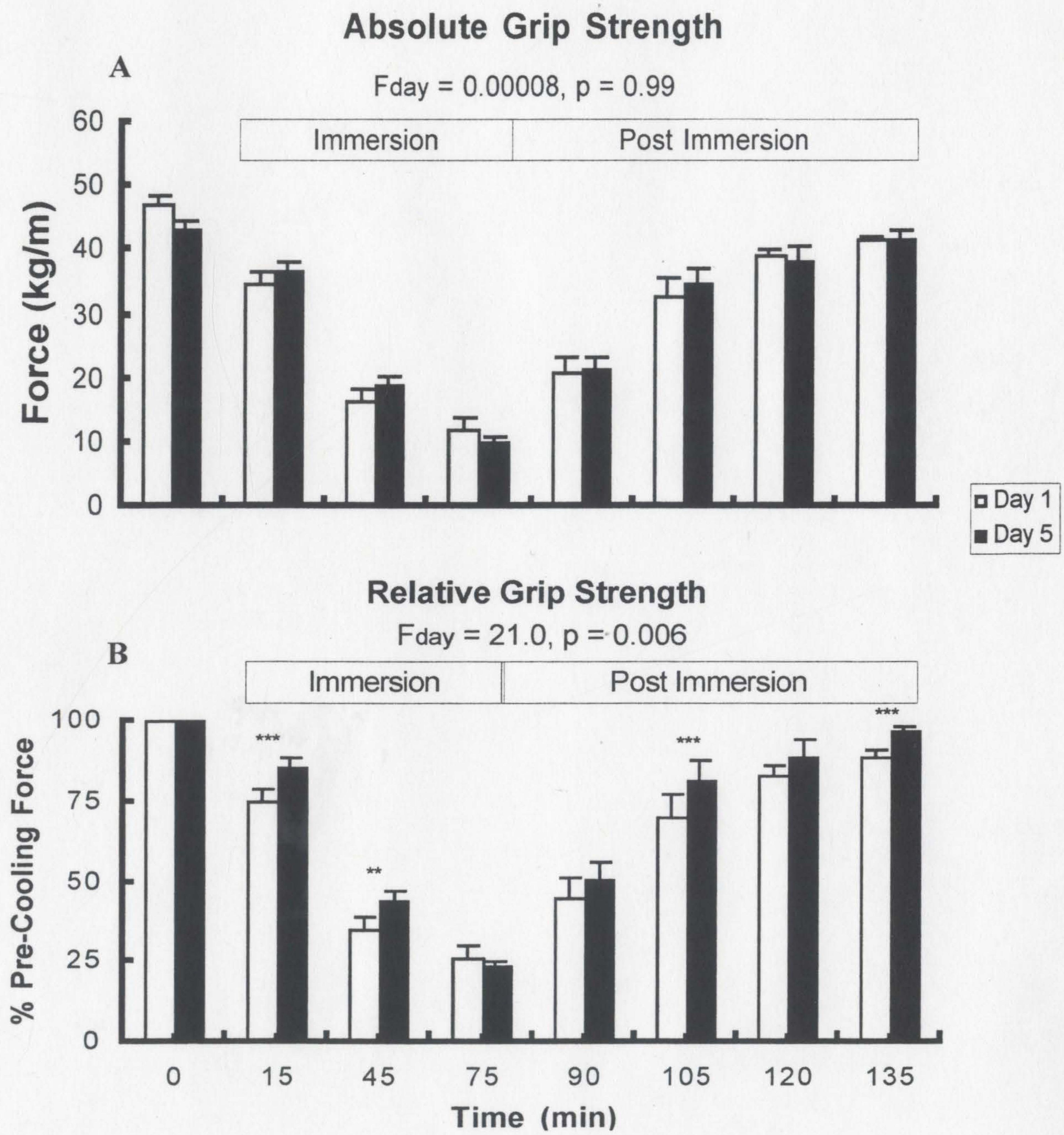
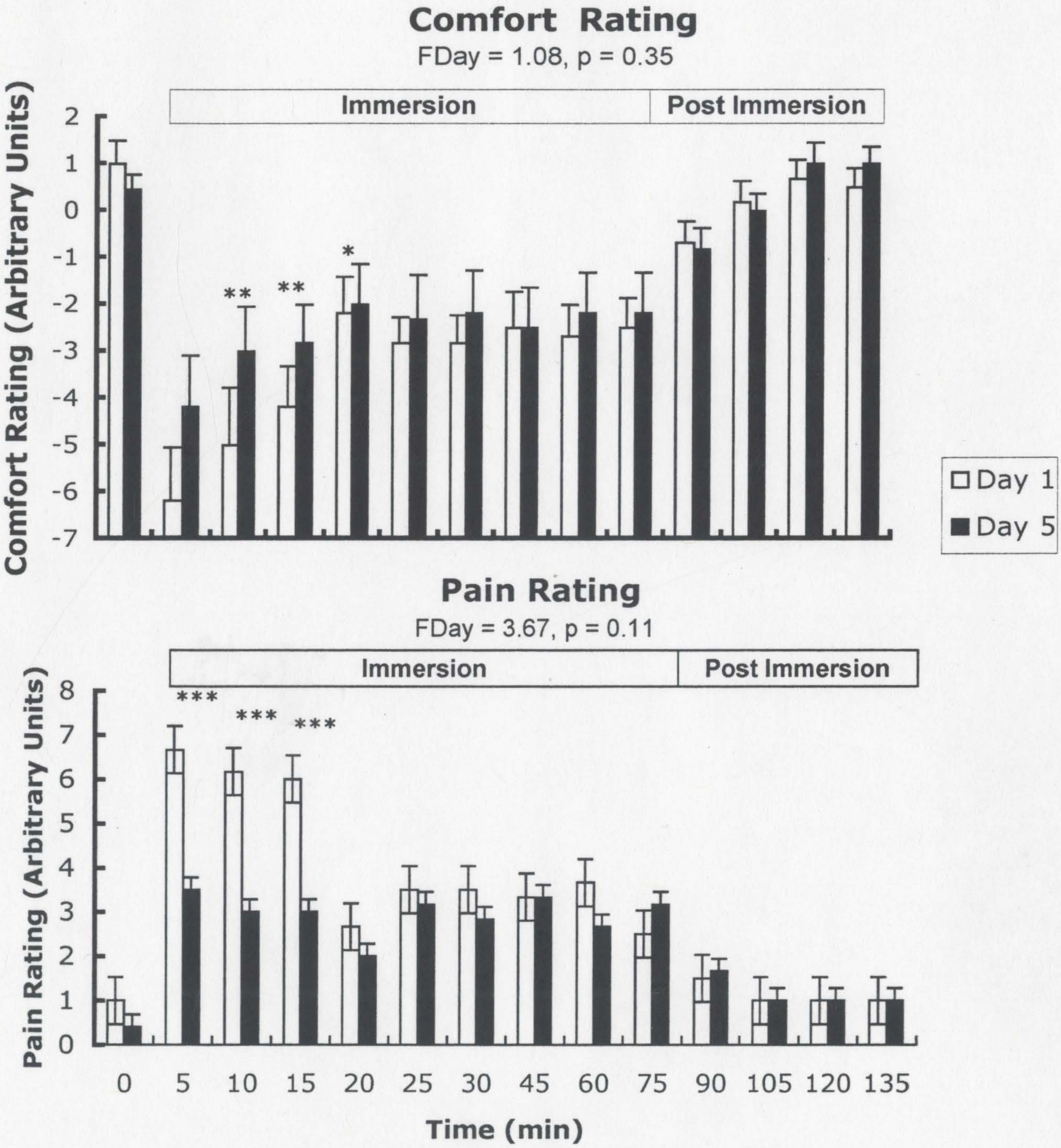


Figure 4.7: Mean comfort and pain levels across Days 1 and 5 prior to immersion at 0 min, until 75 min of immersion and 60 min of recovery following limb immersion in room air. Perceived comfort scale: 2 = Comfortably Warm, -10 = Extremely Cold. Perceived pain scale: 1 = No Pain, 11 = Unbearably Painful. (n= 6 males, * p < 0.05, ** p < 0.01, *** p < 0.001).



Chapter 5: Summary and Conclusions

5.1 Response to Research Hypotheses

Hypothesis 1: Based on the review of the literature, including evidence from the female Ama divers, it was hypothesized females will perform better on manual tasks with limb cooling than males. It was also hypothesized that perceived pain and discomfort would be higher in females than males.

Females did show some improvement on selected fine and gross motor tasks relative to males so this hypothesis was partially supported.

There were no significant differences across gender in perceived pain and comfort, thus the hypothesis that females will have greater perceived pain and discomfort with limb cooling was rejected.

Hypothesis 2: It was hypothesized that after a 5-day acclimation to upper limb cold-water immersion, there would be significantly improved strength and performance on fine and gross motor tasks. Perceived pain and discomfort were hypothesized to be lower after 5 days of acclimation.

There was partial support for the hypothesis that 5 days of upper limb cold-water immersion will improve that fine and gross motor task performance. Some evidence of improved fine motor tasks and grip strength was evident.

Acclimation resulted in a significant improvement in perceived pain and comfort on Day 5 during the initial minutes of immersion as compared to Day 1. Our findings support the hypothesis that acclimation over 5 days and at this level is sufficient to bring on an improved perception of a cold limb stress.

5.2 Responses to Testable Questions

Chapter 3: Gender Comparison

1. Is there a gender difference in fine and gross motor task performance during and following 75 minutes of cold-water immersion of the dominant upper limb?

The results of the investigation in Chapter 3 of this thesis support that there were selected fine and gross motor tasks when females showed smaller decrements than males during and following upper limb cooling in an 8°C water bath. However, for the majority of fine and gross motor tasks and for upper limb strength corrected for pre-cooling differences in strength, males and females gave the same decrements in performance on these tasks.

2. Is there a gender difference in perceived pain and comfort during and following 75 minutes of cold-water immersion of the dominant upper limb?

The results of the investigation in Chapter 3 of this thesis do not support that there were any differences across gender for perceived pain and comfort during 75 minutes of cold (8°C) water immersion of the dominant upper limb or during 1 hour of recovery following immersion.

Chapter 4: Local Acclimation to Cold

1. For males after 5 days of acclimation, is there a difference in fine and gross motor task performance during and following 75 minutes of cold-water immersion of the dominant upper limb?

The results show limited evidence of cold local acclimation for fine motor tasks and grip strength, but not for gross motor tasks prior to, during, or after repeated upper limb immersion in 8°C water.

2. For males after 5 days of acclimation, is there a difference in perceived pain and comfort during and following 75 minutes of cold-water immersion of the dominant upper limb?

Perceived pain and comfort showed limited but significant improvements at the start of a cold acclimation during the first 15 to 20 min of immersion. Following the first 15 to 20 min of immersion, the ratings of perceived pain and comfort were not significantly different between days 1 and 5 of the cold acclimation study.

Chapter 6: Overall Thesis References (Alphabetical)

Overall Thesis References (Alphabetical)

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