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ORIGINAL ARTICLE

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# Effect of cold-induced vasodilatation in the index finger on temperature and contractile characteristics of the first dorsal interosseus muscle during cold-water immersion

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**Abstract** We investigated whether cyclic elevations in index finger temperature (cold-induced vasodilatation, CIVD) during prolonged cold exposure correlated with hand temperature and neuromuscular function. Evoked twitch force of the first dorsal interosseus (FDI) muscle was measured every minute in eight males and four females [age 25.4 (5.7) years, mean (SD)] during cooling of the hand for 30 min in 9°C water, and in thermoneutral 30°C water. During cooling, index finger temperature increased from 9.4 (0.9)°C at the nadir to 13.3 (2.4)°C ($P<0.01$) at the apex of the CIVD. However, the minimum skin temperature above the FDI muscle was 14.2 (2.1)°C, with no CIVD detected in any of the subjects. Peak twitch force was 2.5 (0.7) N at the nadir of the finger CIVD and 2.0 (0.8) N at the apex ($P=0.07$), time-to-peak increased from 189 (18) ms to 227 (26) ms ($P<0.01$), and half relaxation time increased from 135 (14) ms to 183 (32) ms ($P<0.01$). We conclude that CIVD is a local phenomenon isolated to the fingers, and that it does not have beneficial effects on either temperature or neuromuscular function of the FDI muscle during cold exposure.

**Keywords** Hand · Skin temperature · Evoked force · Contractile properties · Cold-induced vasodilatation

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## Introduction

When exposed to cold stress, the body responds with a vasoconstriction in the extremities to maintain the temperature in the core. After several minutes of vasoconstriction, a paradoxical cycling of vasodilatation and vasoconstriction will occur. This cold-induced vasodilatation (CIVD) or 'hunting response' (Lewis 1930) is typically reported in extremities such as the finger (Keatinge 1957; Lewis 1930), hand (Chen et al. 1996; Daanen et al. 1997), feet (Fox and Wyatt 1962; Greenfield et al. 1951), and ears and cheeks (Fox and Wyatt 1962), though more proximal body parts have also been reported to demonstrate CIVD. Fox and Wyatt (1962) found increases in skin temperature during cooling of the forearm and calf, and Ducharme et al. (1991) also showed cyclic intramuscular temperature fluctuation during forearm cooling. During CIVD, blood flow has shown oscillatory changes similar to finger skin temperature, with blood flow changes preceding skin temperature changes by about 2 min (Daanen and Ducharme 1999). The increase in blood flow raises the temperature of the periphery, with index finger temperature increasing after about 15 min from 3°C up to as much as 12°C in healthy individuals (Lewis 1930). CIVD may be considered as a protective response for minimizing the risk of cold injury (Wilson and Goldman 1970) in the fingers and other distal peripheral tissues.

Cheung et al. (2003) reported a rapid and progressive impairment in both hand temperature and fine manual dexterity even with short-term hand and forearm immersion of 2–5 min in cold (10°C) water, supporting a close linkage between hand and finger temperature and manual function (Giesbrecht and Bristow 1992; Heus et al 1995). With a decrease in muscle temperature, contraction velocity decreases and relaxation rate increases, maximal force decreases (Bigland-Ritchie et al. 1992; Ranatunga et al. 1987), and the muscle is less powerful (De Ruiter and De Haan 2000). Additionally, tactile sensitivity also decreases rapidly with hand and finger cooling (Provins and Morton 1960), resulting in greater digit grip force required to perform pre-planned movements (Nowak and Hermsdorfer 2003). If CIVD increases temperature in both the hand and fingers, besides a possible cryoprotective role, an additional benefit of CIVD may be to maintain manual performance by improving muscle function and tactile sensitivity in the cold.

The purpose of this study was therefore to investigate the effects of cold-water immersion on both the CIVD response of the index finger and its major abductor muscle, the first dorsal interosseus (FDI), and to determine whether local temperature changes in the hand influenced the contractile properties of the FDI. We measured finger and FDI temperature during hand immersion in cold (9°C) water recording muscle function during peaks and nadirs of the finger CIVD cycle. It was hypothesized that the increase in blood flow during the peak of the CIVD would warm up the hand and fingers and improve the neuromuscular function of the FDI muscle, resulting in a higher peak twitch force, and a smaller time to peak and half relaxation time.

## Methods

### Subjects

Fourteen volunteers initially participated in this study. All participants were non-smokers and were screened for circulatory diseases such as Raynaud's phenomenon. The Ethics Committee of the University of New Brunswick approved the study protocol in advance. Each subject completed and answered 'no' to all questions on the Physical Activity Readiness Questionnaire (Canadian Society for Exercise Physiology 1998), a standard questionnaire inquiring for cardiovascular and neuromuscular health problems, and provided written informed consent before participating. Two female subjects did not show a cold-induced vasodilatation in the index finger, defined as an increase in skin temperature of the index finger of more than 0.5°C. Therefore, their data were excluded from analysis. The analysis was performed on the twelve remaining subjects [eight males, four females, 25.4 (5.7) years], all Caucasian with the exception of one East Indian female.

### Research design

A repeated-measures experimental design was used to test the direct effects of CIVD on evoked force of the FDI muscle. The experimental protocol was performed twice over two different sessions: an experimental (Cold) and a thermoneutral (CON) condition, with the order of presentation of the conditions counterbalanced. Each subject served as his or her own control. During the 30-min water immersion, a twitch was evoked every minute. Twitches occurring at the time of the nadir and apex of the CIVD in the Cold condition were subsequently used for analysis and matched with twitches occurring at the same time of water immersion in the CON condition.

### Experimental protocol

Upon arrival at the laboratory [room temperature 22.7 (2.6)°C; mean (SD)], the subject was instrumented with two ceramic chip skin thermistors (MA-100, Thermometrics, Edision, N.J.) placed next to the nail bed of the right index finger (to measure temperature of index finger, $T_{if}$) and on the skin above the FDI muscle ($T_{fdi}$). Temperature was logged every 12 s on a data logger (Smartreader 8 Plus, ACR, Vancouver, Canada) interfaced with a computer so that the skin temperature could be monitored continuously. Two stimulating electrodes were placed over the ulnar nerve, 4 and 7 cm proximal to the pisiform bone. The subject was seated comfortably with their upper arm abducted, and the forearm resting on a stable base. The right hand, covered with a thin rubber glove, was placed on a plateau in the climatic box containing a myograph (Fig. 1). The right index finger was placed and immobilized next to a strain gauge force transducer [Honeywell Sensotec, Columbus, Ohio, model 31, capacity 5 lbs (2.27 kg)] to ensure minimal compliance. The hand was immobilized with a clamp inside the myograph. Supramaximal square wave pulses of 200 μs duration were delivered through the two stimulating electrodes by a constant current stimulator (Digitimer, DS7A, Hertfordshire, UK). In each session, the intensity of the supramaximal current was determined by increasing the current until no further increase in force output was detected. The intensity of the current was not significantly different between the two sessions [62.1 (9.6) mA, Cold, versus 68.3 (11.9) mA, control condition]. The resulting abduction force was amplified (×100) and collected at 1 kHz for

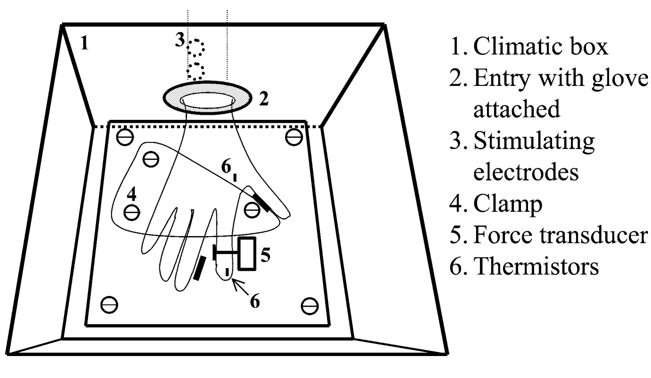


**Fig. 1** Custom-made myograph

later processing (WinDaq Pro+, Dataq, Ohio). The water in the myograph box was maintained at 9.0 (0.4)°C with a recirculating chiller (Polyscience, Niles, Ill.).

Once the hand was secured in the myograph and the supramaximal stimulus intensity was determined, the first twitch was evoked and recorded. Immediately after evoking the first twitch, the timer was started and the water level in the climatic box was raised until the hand and wrist were 2 cm under water. Every minute a twitch was evoked until the completion of 30 min. Every 5 min, subjective thermal sensation and comfort were measured. The scales used were modified from Gagge et al. (1967). The ratings for thermal sensation ranged from 0 (unbearably cold) to 9 (very hot), with 5 as neutral. The thermal comfort scale ranged from 1 (comfortable) to 5 (very uncomfortable), with increments of 0.5.

### Data analysis

The following characteristics were calculated from the evoked force measurements. Peak twitch force (PTF) of the twitch was defined as the peak amplitude of the force signal. Time to peak force (TTP) was defined as the delay between the stimulus and the peak amplitude. The half relaxation time (HRT) was defined as the time between the PTF and the point at which the peak force was reduced to half its size.

The nadir of the CIVD was defined as the lowest temperature before the index finger temperature increased by more than 0.5°C, and the apex of the CIVD was defined as the highest temperature after the nadir. The temperatures at the time of the twitches closest to the nadir and apex were used for calculations of nadir and apex temperatures. The average temperatures of the index finger and the FDI were calculated over the full 30 min water immersion.

The thermal ratio ($R_{10}$)—analogue to $Q_{10}$ (thermal coefficient)—was calculated for PTF, TTP, and HRT with the average data of all subjects. $R_{10} = (S_1/S_2)^{(10/T_2-T_1)}$ with $S_2$ and $S_1$ as quantities, respectively, at temperatures $T_2$ and $T_1$, and $T_2 > T_1$ (Bennett 1984). For $T_1$ and $T_2$, $T_{\mathrm{fdi}}$ was used. Also, a one-way ANOVA with repeated measures (FDI temperature) was performed on the twitch characteristics at FDI skin temperatures of 14, 15, 16, and 17°C, to investigate the change in neuromuscular function with the increase in $T_{\mathrm{fdi}}$.

For the neuromuscular data, the twitch characteristics at four distinct times were used for the analysis: the initial twitch, the twitch at the nadir and apex of the CIVD and the final twitch (min 30). A two-way ANOVA (condition × time) with repeated measures on one factor (time) was used to test for differences in responses between temperatures and across time. Bonferroni post-hoc tests were applied to determine significance between individual means. The correlation between the $T_{\mathrm{fdi}}$ and the three twitch characteristics were tested using a Pearson Product Moment correlation, with alpha set at 0.05.

## Results

### Thermoregulatory data

$T_{\mathrm{if}}$ decreased from 29.5 (3.1)°C to 9.5 (1.1)°C at the nadir, then increased to 13.3 (3.6)°C during the CIVD, and decreased again to 12.1 (2.0)°C in the final stage of immersion. The nadir and apex of the CIVD occurred at 1,039 (198) s (17 min 19 s) and 1,535 (227) s (25 min 35 s) respectively. The amplitude of the CIVD was 3.8 (2.6)°C. The average temperatures of the index finger and FDI were 14.4 (4.4)°C and 19.0 (3.2)°C respectively.

$T_{\mathrm{fdi}}$ decreased from 31.5 (1.8)°C to 14.1 (2.1)°C with no increase in FDI temperature observed at the time of the CIVD in the index finger. There was no significant change in finger or FDI temperature during the water immersion in the CON condition.

### Neuromuscular data

PTF decreased gradually with immersion time from 3.0 (1.0) N to 1.8 (0.8) N after 30 min. TTP and HRT increased from 135 (60) ms to 235 (22) ms, and 73 (10) ms to 189 (34) ms, respectively. Fig. 2 shows the evoked twitches at the four different stages during the 30 min water immersion in the Cold condition.

There was no improvement of neuromuscular function at the time of the CIVD apex. In Fig. 3, both temperature and muscle characteristics during the 30 min of cold-water immersion are displayed. There was a significant difference between the Cold and CON conditions for both $T_{\mathrm{if}}$ and $T_{\mathrm{fdi}}$, as well as for PTF, TTP, and HRT ($P < 0.05$), in stages 2, 3 and 4. There was also a significant difference between the four stages for all

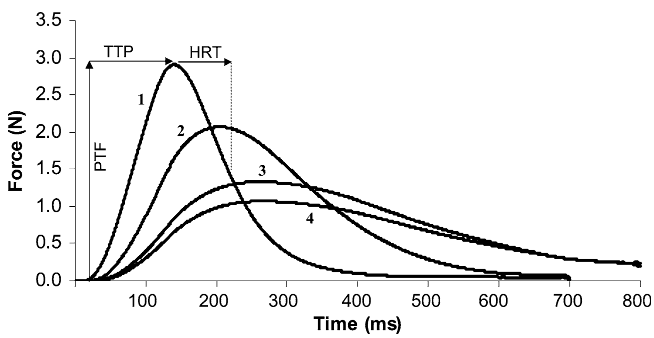


**Fig. 2** An example of evoked twitch force of one subject at four different stages of the cold water immersion of the hand. *1* Initial [right index finger temperature ($T_{if}$) = 29.5°C, and skin temperature above the first dorsal interosseus ($T_{fdi}$) = 31.5°C], *2* nadir cold-induced vasodilatation (CIVD) ($T_{\mathrm{if}}$ = 9.5°C, $T_{\mathrm{fdi}}$ = 17.2°C), *3* apex CIVD ($T_{\mathrm{if}}$ = 13.3°C, $T_{\mathrm{fdi}}$ = 14.8°C), *4* final ($T_{\mathrm{if}}$ = 12.1°C, $T_{\mathrm{fdi}}$ = 14.1°C)

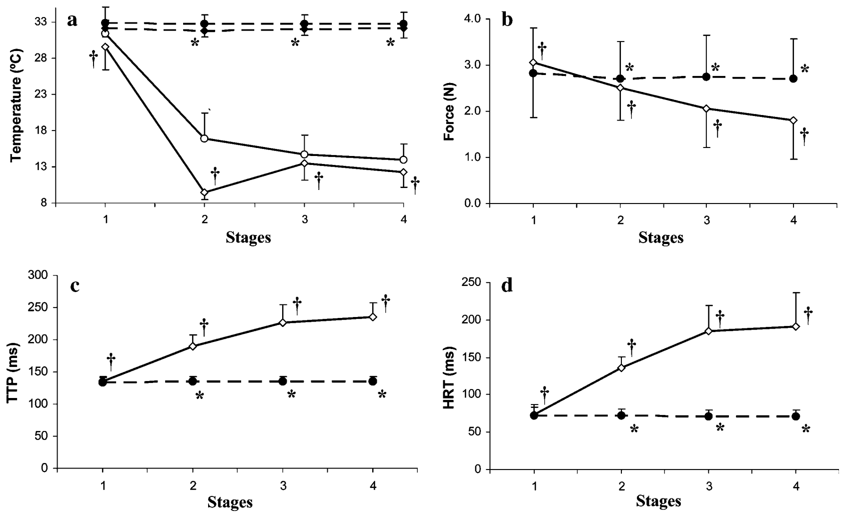


**Fig. 3a** Average $T_{if}$ (*diamonds*) and $T_{fdi}$ (*circles*) at four different stages (*1* initial, *2* nadir, *3* apex CIVD, *4* final) during the 30 min of water immersion. **b** Peak twitch (*PTF*) at the four stages of water immersion. **c** Time to peak (*TTP*) at the four stages of water immersion. **d** Half relaxation time (*HRT*) at the four stages of water immersion. *Continuous line* Experiment carried out in cold condition, *dashed line* control condition. † Significant difference between stages ($P < 0.05$), *significant difference between conditions ($P < 0.05$)

muscle characteristics ($P < 0.05$) during cold-water immersion.

During the cold-water immersion, there was a high correlation between the $T_{fdi}$ and the three twitch characteristics. The correlation between $T_{fdi}$ and PTF was $r = 0.42$ ($P < 0.01$). The correlation between $T_{fdi}$ and TTP and HRT were $r = -0.64$ ($P < 0.01$) and $r = -0.64$ ($P < 0.01$), respectively.

The $R_{10}$ values for PTF, TTP, and HRT were, respectively, 1.51, 0.61, and 0.44 for $T_{fdi}$ between 14°C and 24°C, and decreased for PTF to 1.1, and increased for TTP and HRT to 0.86 and 0.76, between 21°C and 31°C.

### Thermal sensation and thermal comfort

Thermal sensation decreased significantly from 5.5 (1.1) (neutral) before cold-water immersion to 2.0 (0.6) (cold) after 5 min to 1.0 (0.8) (very cold) after 15 min ($P < 0.01$). Thermal comfort decreased significantly from 1.0 (0.0) (comfortable) before cold-water immersion to 2.4 (0.6) after 5 min ($P < 0.01$), and was significantly different from before after 20 min [3.7 (0.8), $P = 0.04$]. The average ratings of thermal sensation and thermal comfort during 30 min of water immersion in cold and CON condition are shown in Fig. 4. There was a significant difference in the ratings of thermal sensation and thermal comfort between conditions at all times, except immediately prior to the immersion (0 min) ($P < 0.01$).

## Discussion

This is the first study to directly examine the effect of CIVD in the fingers on the contractile characteristics of a hand muscle, specifically the FDI. It was hypothesized in the present study that the increase of blood flow to the fingers would also warm up the FDI and improve its function during hand immersion in 8°C water. Instead, no CIVD response was observed in the skin temperature above the FDI, which gradually decreased over the immersion period and was possibly related to the overall deterioration of the twitch characteristics.

While one might expect that the index finger would typically be colder than the FDI because blood has to pass through the more proximal parts of the hand losing heat through convection along the way, we found that

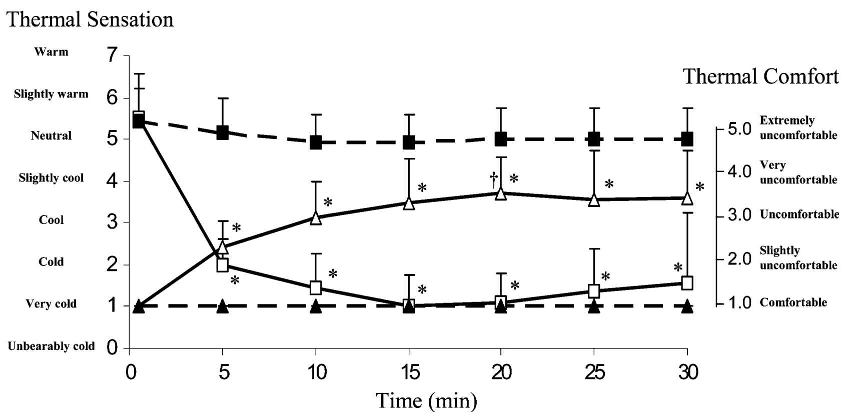


**Fig. 4** Ratings of thermal sensation (*squares*) and thermal comfort (*triangles*) during 30 min water immersion in cold water (*continuous line*) and warm water (*dashed line*). *Significant difference between conditions ($P < 0.01$), † significantly different from value at 5 min ($P < 0.05$)

the index finger temperature was higher at the apex of the CIVD than the FDI temperature. Grant and Bland (1931) found the least rise in temperature on the dorsal and most proximal points on the finger when immersed in ice water. They suggested that the arrangement of the small vessels in the fingers are such that the veins draining the finger run chiefly on the dorsal surface so that the more proximal part of the finger is warmed mainly by the blood returning from the tip. Another explanation of the quick response of index finger temperature may be the higher density of arteriovenous anastomoses in the nail bed compared to the dorsum of the hand (Grant and Bland 1931). This, together with the smaller volume of the index finger compared to the volume of the FDI, could explain the discrepancies between the index finger temperature and the temperature of the FDI during CIVD. A muscle on the palmar side of the hand may have shown a larger amplitude in CIVD, and therefore be affected more by this increase in temperature. The reason the FDI muscle was chosen was because of its primary responsibility for abduction of the index finger (Keen et al. 1994), which is essential in gripping. The FDI is also involved in flexion of the metacarpophalangeal joints of the index finger, but so are several other muscles.

In the present study, $T_{\mathrm{fdi}}$ was measured as an index of FDI muscle temperature. Ducharme et al. (1991) measured intramuscular temperature gradients of the forearm during their prolonged cooling protocol, and reported that the fluctuations in temperature at the longitudinal axis of the forearm were not reflected in skin temperature. Therefore, it remains possible that the surface measurement we used to estimate FDI temperature did not accurately reflect FDI muscle temperature. However, this is unlikely, as the FDI muscle is a much smaller muscle compared to the muscles in the forearm, and other researchers have previously demonstrated a close and linear relationship ($r=0.97$) between the $T_{\mathrm{fdi}}$ and muscle temperature 0.5–0.7 cm within the FDI (Ranatunga et al. 1987). De Ruiter et al. (1999) also showed a close and linear relationship between skin and muscle temperature of the adductor pollicis muscle, which is another small hand muscle. In addition, there was a high correlation between the contractile characteristics of the FDI and the $T_{\mathrm{fdi}}$ consistent with what would be expected in a cooled muscle. Ranatunga et al. (1987) found increases of 3.6 ms and 2.5 ms for time to peak and half relaxation time, respectively, per 1°C decrease in $T_{\mathrm{fdi}}$. This is not surprising since neuromuscular function is temperature dependent (De Ruiter et al. 1999; Ranatunga et al. 1987). Although the hand was immobilized for 30 min in the myograph, it is unlikely that this would have had an effect on the results since there were no changes in temperature response or contractile characteristics during the CON condition.

It is possible that electrical stimulation changes the vasomotor response in the hand, but because only a single stimulus was used, and no vasoconstriction was seen in the CON condition, this is not likely. This study investigated the twitch characteristics, while neuromuscular function is not only a function of muscle function, but also of efferent drive and synaptic transmission. It is known that conduction velocity is decreased with a decrease in temperature (De Jong et al. 1966), but because the distance from the point of stimulation to the effector muscle is relatively short, this effect is negligible. Synaptic transmission and the neuromuscular junction are also temperature sensitive (Rutkove 2001). Cooling decreases the speed of acetylcholine release, which affects synaptic transmission, but this is partially counteracted by increased sensitivity of the postjunctional membrane to acetylcholine caused by cooling (Foldes et al. 1978).

$Q_{10}$ and $R_{10}$ give information about the temperature dependence of, respectively, the rate process (such as rate of force development or relaxation) and quantities (such as peak force) measured. PTF seems the most dependent on temperature with an $R_{10}$ value of 1.51, meaning that an increase in $T_{\mathrm{fdi}}$ from 14°C to 24°C will increase PTF by a factor of $\sim$1.5. At higher temperatures, the $R_{10}$ value for PTF decreased, while $R_{10}$ for TTP and HRT increased. This is to be expected because in cold conditions PTF will decrease in value, while TTP and HRT will increase. The $R_{10}$ values are smaller than the $Q_{10}$ values mentioned for rate of force development and relaxation (De Ruiter et al. 1999). This is in agreement with values mentioned in Bennett (1984). Twitch characteristics have a direct relationship with the $T_{\mathrm{fdi}}$ (Ranatunga et al. 1987). Further analysis showed that an increase in $T_{\mathrm{fdi}}$ of only 1°C, from 14°C to 15°C, significantly improved neuromuscular function. We did not find an increase in FDI temperature during CIVD and, unfortunately, most research mentions $T_{\mathrm{if}}$ only, and not temperature of any hand muscles.

The subjects rated themselves colder and less comfortable during the cold-water immersion as expected. There was, however, no improvement seen during the CIVD, although both thermal sensation and thermal comfort leveled off after about 20 min. It is possible that the interval of 5 min between measurements was too large to detect changes in subjective ratings during CIVD. Kreh et al. (1984) measured subjective pain sensations during finger cooling in 0°C at an interval of 12 s. They found that pain seemed to be inversely related to the finger-pulse amplitude. There is however a difference between feeling pain and feeling cold. The subjects may have felt relieved of pain during CIVD, but still have rated themselves cold. Sawada et al. (2000) concluded that at such low temperatures, subjective judgement may not be reliable for monitoring the risk of progressive tissue cooling and frostbite formation.

In summary, the CIVD observed in the index finger was not matched by either a CIVD response in $T_{\mathrm{fdi}}$ or any improvement in neuromuscular function of the FDI during immersion of the entire hand for 30 min in 9°C water. Instead, $T_{\mathrm{fdi}}$ gradually decreased over the immersion period, and the deterioration of the twitch characteristics during cooling was not halted or improved throughout cooling. It is possible that CIVD of the fingers is primarily a local cryoprotective finger response that does not correlate with overall hand thermoregulation or serve to enhance neuromuscular function of the hand.

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