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ORIGINAL ARTICLE

Influence of body dimensions and sex on cold-induced vasodilation

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Abstract

Cold-induced vasodilation (CIVD) is a physiological response characterized by cyclic vasodilation occurring within 5–10 min of cold exposure, predominantly in the fingers and toes. This study aimed to determine the roles of body dimensions, specifically surface-to-mass (SM) ratio and sex in modulating CIVD responses. Thirty-nine participants (mean ± SD age: 24 ± 3 yr; height: 174 ± 28 cm; weight: 75.3 ± 15.2 kg; 20 males & 19 females) completed a 30-min immersion of the digits in ice water while sitting in a thermoneutral room (22 °C). Skin temperature was measured continuously on the anterior pads of the index, middle, ring, and little finger to assess CIVD parameters (onset time (t_{onset}), minimum finger temperature (T_{min}), maximum finger temperature (T_{max}), mean finger temperature (T_{mean}), and $CIVD_{waves}$). A negative relationship was observed between T_{max} and SM ratio ($r = -0.39$, $p = 0.001$) and T_{mean} and SM ratio ($r = -0.32$, $p = 0.001$), indicating that individuals with smaller SM ratios exhibited enhanced CIVD responses. A subgroup of 7 males and 7 females with identical anthropometrics from the original cohort showed no differences between any CIVD parameter: T_{mean} (Males: 8.0 ± 1.9 °C; Females: 8.9 ± 1.6 °C, $p = 0.36$), T_{max} (Males: 11.2 ± 3.1 °C; Females: 13.1 ± 1.2 °C, p = 0.16), T_{min} (Males: 5.9 ± 1.4 °C; Females: 5.0 ± 1.7 °C, $p = 0.31$), and t_{onset} (Males: 12.0 ± 4.4 min; Females: 9.6 ± 3.6 min, $p = 0.28$). Therefore, body dimensions seem to play a crucial role in modulating CIVD responses, whereas sex does not.

Keywords Hunting reaction · Surface-to-mass ratio · Finger skin temperature · Cold stress · Bergmann's rule · Allen's rule

Abbreviations

AVAs	Arteriovenous anastomoses
BMI	Body mass index (kg/m2)
BSA	Body surface area (m^2)
CIVD	Cold-induced vasodilation
HR	Heart rate
P_{hand}	Hand pain sensation
RFL	Relative finger length
RFW	Relative finger width to body mass (cm/kg)
RIF	Resistance index of frostbite
SD	Standard deviation
SM	Surface-to-mass ratio
T_{ampl}	Temperature amplitude (°C)
T_c	Core temperature (°C)
TC	Thermal comfort
T_{max}	Maximum finger temperature (°C)
T_{mean}	Mean finger temperature (°C)
T_{min}	Minimum finger temperature (°C)
t_{onset}	Vasodilation onset time
$CIVD_{waves}$	# Of complete CIVD waves during immersion
TS_{hand}	Hand thermal sensation
WT	Weight (kg)

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Introduction

Given that humans evolved near the equator, it is no surprise that their physiological defenses against heat stress are superior to their defenses against cold stress. However, humans maintain some unique physiological adaptations that are beneficial in cold environments. The cold-induced vasodilation (CIVD) response is a cyclic opening of the blood vessels that has generally been observed within 5–10 min of local cold exposure (Daanen 2003). It occurs predominantly in the fingers and toes and can provide oscillations of warmer blood, thereby improving manual dexterity and decreasing pain when exposed to cold (O'Brien 2005). CIVD

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frequency, magnitude, and/or onset time (t_{onset}) varies considerably between individuals (Daanen and van der Struijs 2005; Yasukochi et al. 2023) and may be influenced by several factors, including but not limited to age, sex, fitness, mental stress, diet, smoking, body dimensions, and cold adaptation (Cheung 2015; Daanen 2003).

CIVD offers both advantages and disadvantages in cold environments. CIVD is determined by the opening and closing of arteriovenous anastomoses (AVAs), which are essential in human thermoregulation (Bergersen 1993). CIVD has shown to prevent cold injuries like frostbite by increasing blood flow to extremities and preserving dexterity and tactile sensitivity (Daanen 2003). However, this response also increases peripheral heat loss, which may contribute to hypothermia, specifically in severe cold (Flouris et al. 2008). Thus, while CIVD offers localized benefits to the fingers and toes, it can pose risks for core temperature regulation during prolonged cold exposure.

According to the ecogeographical principle 'Allen's rule', homeothermic animals living in cold climates have shorter yet thicker limbs and extremities to retain heat, while those living in warmer climates have longer limbs, and thus a greater surface area to release heat (Allen 1877). Similar relationships between environmental conditions, body mass, and extremity length have been shown in humans (Pomeroy et al. 2021). For example, those originating from high-latitude Arctic environments display shorter and thicker finger length as an adaptation to minimize heat loss by reducing the surface area exposed to the cold (Betti et al. 2015). Additionally, Bergmann's rule states that larger body mass animals are predominantly found in cold environments, while smaller animals of the same species inhabit warm environments (Bergmann 1847). The same can be observed in humans where those originating from polar regions tend to have a larger body mass than those in mid-latitudes that increases heat content (Holliday and Hilton 2010).

The underlying mechanism that supports Bergmann's and Allen's rules during cold exposure resides in the surface-to-mass (SM) ratio and its implication on heat loss. In general, a larger total body mass would generate more heat and have enhanced tissue insulation (Glickman-Weiss et al. 1993) that could improve CIVD, as CIVD is strongly influenced by the thermal state of the body (Flouris and Cheung 2009). Whole-body cooling delays CIVD onset (Daanen et al. 1997; Keatinge 1957), while increased body heat content improves the CIVD response (Daanen et al. 1997). However, a large surface area results in greater heat loss due to conduction, convection, radiation, and/or evaporation. A low SM ratio (i.e., large body mass with a small surface area) would lead to minimized heat dissipation resulting in improved heat conservation and core temperature (T_c) maintenance (Terrien et al. 2011; Wells 2002). In accordance with Bergmann's and Allen's rule, a larger body size with shorter and thicker extremities would lead to a beneficial smaller SM ratio in cold climates. Thus, people with relatively small SM ratios, as commonly observed in cold regions, likely exhibit better CIVD responses than people with relatively large SM ratios.

Potential differences in CIVD responses between males and females can be attributed to anthropometric differences and although not definitive, also to sex. It is thought that sex does have an influence on CIVD, but the current state of the literature warrants more investigation into this topic. To evaluate sex differences only, the body dimensions of the males and females under investigation have to be similar. Since males generally have a larger body mass than females (Schorr et al. 2018), larger and thicker fingers (Jay and Havenith 2004), and longer palm length and hand width (Greiner 1991) compared to females, an unbiased sex comparison in the literature is lacking.

Basal cutaneous blood flow is lower in females in both thermoneutral and cold conditions compared to males (Bollinger and Schlumpf 1976; Cooke et al. 1990; Pollock et al. 1993) while smaller hands are prone to more pronounced vasoconstriction (Wouda 1977). In line with this, finger skin temperatures during cold stress are lower in females compared with males (Bartelink et al. 1993). Similar differences between males and females are observed in the feet, as Lunt & Tipton (2014) found the feet of females to cool faster than males. Thus, it could be expected that CIVD responses would be weaker in females, but it is not known if this is due to their body dimensions or sex only. Others, however, report no sex differences in CIVD parameters (Miller et al. 2019; Tsoutsoubi et al. 2022; Tyler et al. 2015), highlighting the inconsistencies in the literature that are likely related to anthropometric confounders.

The aim of the present study was to evaluate the effect of body dimensions (hand/finger anthropometry and surface-to-mass ratio) and sex on CIVD responses. By constructing a male and female subgroup of similar anthropometry from the entire study sample, we may be better suited to establish sex as a sole contributor to performance decrements and increased frostbite risk. This information could then be used to develop focused programs to prevent cold injury. We hypothesized that 1) those who have smaller SM ratios will show an enhanced CIVD response, 2) those with shorter and thicker fingers will have an enhanced CIVD response, and 3) males will exhibit a higher magnitude of CIVD and experience a faster onset time compared to females, indicating a stronger CIVD response.

Methods

Participants

Twenty male and nineteen female participants (mean ± SD age: 24 ± 3 yr; height: 174 ± 28 cm; weight: 75.3 ± 15.2 kg) volunteered for the study. In compliance with the Standing Committee on Science and Ethics at Vrije Universiteit Amsterdam (VU) (Protocol# 2023-02R1), all participants provided voluntary informed consent and the study was conducted in accordance with the amended Declaration of Helsinki. All participants were moderately active, non-smokers and not acclimatized to cold environments based off self-reported questionnaires. The self-reported questionnaires asked health questions dating back 3 months from the day of testing, thus allowing acclimatization status to be determined. Additionally, they had no history of local cold injuries, Raynaud phenomenon, or prescription medication use that would impact vasomotion. All participants were of white ethnic background (The Netherlands = 33, Belgium = 1, Germany = 1, United States of America = 3, and Canada = 1). Participants were asked to abstain from drinking alcohol, strenuous physical activity, and any form of tobacco or caffeine for 12 h prior to the tests, and refrain from food for 3 h prior to the tests. The menstrual cycle and use of contraceptives (e.g., oral contraceptives, intrauterine device, and patch) on testing days were recorded. Hand sizes from Greiner (1991), who measured approximately 1000 males and 1300 female's hands and fingers, were similar to ours, thus highlighting our sample to be "typical" between sexes.

Setup and participant instrumentation

Participants were instrumented with thermocouple sensors (RS PRO type T 1 m, 2 mm diameter) attached to 2 dual-channel thermocouple loggers (Voltcraft, Hirschau, Germany). Prior to use, each thermocouple was calibrated against a known and standard reference thermistor (Greisinger) to allow for accuracy of 0.07 °C. Thermocouples were attached with Fixomull (BSN Medical, Hamburg, Germany) tape to the palmar side of the distal phalanx of digits 2–5 (index, middle, ring, and little) excluding the thumb (digit 1), see Fig. 1 for setup. Finger skin temperature was used to evaluate CIVD responses. Heart rate was measured to monitor cardiovascular and sympathetic responses to cold-water finger immersion using a Polar device (Polar Electro, Finland) that was placed around the torso at the base of the chest. The CORE system (greenTEG AG, Rümlang, Switzerland) is a wearable device that was used to continuously estimate core temperature (T_c) by attaching the sensor to the heart rate chest strap. Prior work has demonstrated good alignment between the CORE system and rectal temperature measurement (Daanen et al. 2023). A thermometer (Greisinger GMH 3750, Regenstauf, Germany) was used to measure and continuously monitor the water temperature during the experiment.

Participants were then provided time to become familiar with hand pain sensation (P_{hand}) (Borg 1998), hand thermal sensation (TS_{hand}), and thermal comfort (TC) scales prior to their use (Gagge et al. 1967). The pain scale for the hand ranged from 0 (No pain at all) to 10 (maximal pain conceivable). Ratings for TS_{hand} ranged from + 4 (very hot) to 0 (neutral) to – 4 (very cold). TC ratings ranged from 0 (comfortable) to 4 (extremely uncomfortable). A nitrile medical exam glove (thickness of 0.08 mm) was then donned and lightly taped at the wrist, careful not to constrict blood flow, to ensure that sensors did not come into direct contact with water during hand immersion. During instrumentation, participants were seated for a minimum of 20–30 min before the first cold-water finger immersion.

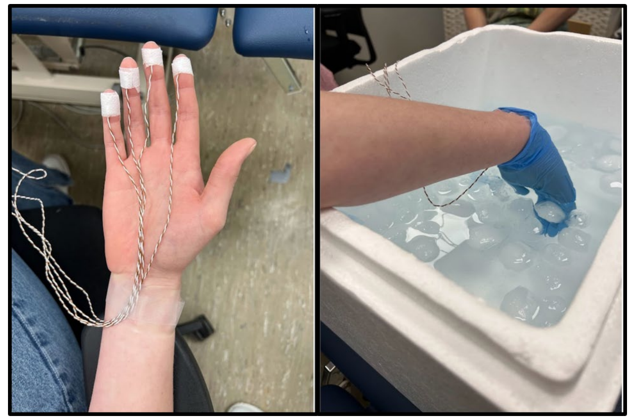

Fig. 1 Thermocouple sensor setup where digits 2–5 were affixed with skin temperature sensors at the distal ends of the fingers (left). Finger skin temperature was collected at a sample rate of 5 s. Photo displaying experimental setup and hand immersion during experimental trial (right)

Protocol

The measurements were performed in April and May 2023 in Amsterdam, The Netherlands. Upon arrival to the laboratory, participants completed a medical history questionnaire and a physical activity questionnaire (IPAQ), including questions related to menstrual cycle for females. Height and weight measurements were taken, and blood pressure was measured using an automatic blood pressure cuff (Omron M6 comfort). Anthropometrics of hand and finger sizes were measured following the procedures from ISO 7250 "Basic human body measurements for technological design" (hand length, index finger length, perpendicular palm length, as well as the width of the proximal and distal phalanx) (Standard 2003).

To ensure similar starting local tissue temperature, the participants first immersed their right hand in warm water (35 ± 1 °C) for 5 min (Tsoutsoubi et al. 2022; Tyler et al. 2015). Immediately after hand immersion in warm water, participants immersed all fingers, except the thumb, for

30 min in ice water up to the metacarpophalangeal (MCP) joint in an indoor environment (22 °C and 40% relative humidity), see Fig. 1. The water temperature was closely monitored and stirred every 2 min, and ice was added to ensure that water temperature remained at 0 °C with occasional small temperature peaks not exceeding 2 °C. Throughout the 30-min cold-water finger immersion, finger skin temperatures were recorded every 5 s and then recalculated to 30-s averages for analysis. A CIVD determination criterion of 0.5 °C (increase in finger temperature of 0.5 °C) was used for 1-min values (O'Brien 2005), and therefore, a 0.25 °C criterion was set for our 30-s values. The following subjective measurements were taken every 2 min: P_{hand}, TS_{hand}, and TC. Finger skin temperature, core temperature, and heart rate were continuously monitored.

CIVD components

CIVD components that define the strength of the CIVD response were calculated for each finger (2nd–5th) using the methods described by Daanen (2003) and included: minimum finger skin temperature (T_{min}; the lowest finger skin temperature just before the onset of CIVD), maximum finger skin temperature (T_{max}: the highest finger skin temperature during the first CIVD wave), CIVD onset time (t_{onset}; the time from start of immersion to T_{min}), mean finger skin temperature (T_{mean}; the average skin temperature during the cold-water immersion excluding the initial 5 min of cold-water immersion), temperature amplitude (T_{ampl}) calculated as the difference between T_{max} and T_{min}, and $CIVD_{waves}$ (frequency of CIVD waves during the 30-min immersion defined by a 1 °C increase and a visible completed wave with an increase and decrease section) (Daanen 2003). A CIVD response was defined as a 0.25 °C uninterrupted increase in finger temperature after T_{min} was reached. The Resistance Index of Frostbite (RIF) was calculated following the method described by Daanen and van der Struijs (2005). RIF scores range from 3 to 9 in which a lower score represents a weak CIVD response, whereas higher scores indicate a strong protective response.

Data analysis

The data of all participants were combined ($N=39$) to evaluate the impact body, hand, and finger anthropometrics had on CIVD components. The relation between finger and hand anthropometrics and CIVD was assessed using correlation analysis. When evaluating anthropometric differences, normality of data was assessed using the Kolmogorov–Smirnov test. Pearson correlations were used for parametric variables, such as average finger temperature. Spearman correlations were used for non-parametric tests, such as for subjective responses. BMI was calculated by dividing the weight by the participant's height in meters squared. Body Surface Area (BSA) was calculated (Du Bois and Du Bois 1989) and subsequently used to calculate the surface-to-mass (SM) ratio, which was determined for every participant by dividing BSA by the participants' respective weight. In line with ISO 7250, index finger length and breadth was measured, which is representative of other finger dimensions. Relative Index Finger Length (RFL) was computed by dividing the index finger length with the respective height of the participants. Similarly, the Relative Index Finger Width (RFW) of every participant was obtained through the ratio of the proximal phalanx width and the body weight. Using these relative measures allowed the pooling of all participants in one group for analysis as it excludes the influence of natural anthropometric differences that are inherent between both sexes.

Independent samples t tests were used to evaluate sex differences for t_{onset}, T_{min}, T_{mean}, T_{ampl}, and $CIVD_{waves}$ using the average of the four fingers (2nd–5th), T_c (immersion average), HR (average of the first 10 min of immersion), P_{hand} (immersion average), TS_{hand} (immersion average), and TC (immersion average). The average of all four fingers' skin temperatures during the 5-min warm water immersion (35 °C) was analyzed using repeated-measures ANOVA to confirm standardized starting skin temperatures prior to each immersion. Data were analyzed to confirm normal distribution using a test of homogeneity of variance. Multiple comparisons were corrected for using the Bonferroni correction.

In the previous analyses, data from all 39 participants were evaluated. For a focused analysis of sex differences, we created a subgroup of 14 participants (7 males and 7 females) selected from the original cohort. These participants were matched based on specific anthropometric measurements (e.g., hand size, body mass, and surface area-to-mass ratio) to control for body size and shape differences between sexes and isolate the effect of sex on physiological responses. Independent samples t tests were used to evaluate sex differences with and without anthropometric matching for t_{onset}, T_{min}, T_{mean}, T_{ampl}, RIF, and $CIVD_{waves}$ using the average of the four fingers (2nd–5th). T tests were also conducted on perceptual measurements: P_{hand} (immersion average), TC (immersion average), and TS_{hand} (immersion average).

All statistical analyses were conducted using Statistical Package for the Social Sciences (SPSS Inc. ®, version 25, Chicago, IL) and GraphPad (PRISM) software. Descriptive statistics (mean ± SD) were calculated for all variables. Statistical significance was defined as $p<0.05$.

Results

Dimensions and hand/finger anthropometrics differences ($N = 39$)

Analyses revealed significant negative correlations between SM ratio and T_{max} ($r = -0.39$, $p = 0.001$), T_{mean} ($r = -0.32$, $p = 0.001$), and CIVDwave ($r = -0.39$, $p = 0.022$) (Table 1, Fig. 2).

Sex differences subgroup ($n = 14$)

There were no significant differences for any CIVD, anthropometric, or perceptual responses between the subgroup of males ($n = 7$) and females ($n = 7$) (Table 2).

Sex differences ($N = 39$)

Prior to immersion (baseline), males displayed warmer fingers (males: 28.1 ± 4.9 °C; females: 25.1 ± 4.1 °C, $p < 0.002$). The average of all four finger skin temperatures during the 5-min warm water immersion (35 °C) was not different between males and females (males: 33.5 ± 1.9 °C; females: 32.5 ± 2.1 °C, $p = 0.13$).

In general, females had smaller body mass and smaller/thinner fingers compared to males (Table 2). Females experienced more pain (males: 3.7 ± 1.8; females: 5.4 ± 2.0, $p = 0.03$), colder TS_{hand} (males: – 2.8 ± 0.7; females: – 3.2 ± 0.6, $p = 0.03$), and worse TC during immersion (males: 1.9 ± 0.7; females: 2.4 ± 0.9, $p = 0.02$). Females also had higher average heart rates (males: 68.7 ± 9.7; females: 76.0 ± 9.4, $p = 0.02$). The right side of Table 2 displays the differences between males and females for CIVD, body dimensions, and perceptual responses when anthropometrics are not controlled.

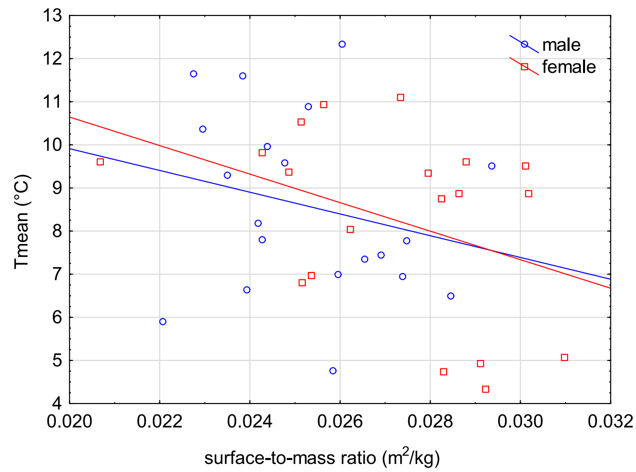

Fig. 2 Relationship between surface-to-mass (SM) ratio and T_{mean} averaged over four fingers further indicating that sex does not play a significant role in T_{mean}. Rather, SM ratio has a larger impact on the regression lines

Discussion

The aim of the present study was to evaluate the effect of body dimensions (hand/finger anthropometry and SM ratio) and sex on CIVD responses. Hypothesis 1 (those who have smaller SM ratios will show an enhanced CIVD response) is accepted, since T_{mean} and T_{max} were higher with smaller SM ratios. Hypothesis 2 (shorter and thicker fingers will have an enhanced CIVD response) is rejected, since thicker fingers showed lower T_{max} values. When evaluating CIVD in the anthropometric matched subgroup, no CIVD parameters (t_{onset}, T_{min}, T_{max}, and T_{mean}) were different between sexes. Thus, hypothesis 3 (males will exhibit a higher magnitude of CIVD and experience a faster onset time compared to females, indicating a stronger CIVD response) is rejected.

The slower cooling rate of males' fingers compared to females' may be attributed to their larger hands providing greater heat content (Jay and Havenith 2004; Lunt

Table 1 Correlations using the average of all four fingers to compare CIVD variables (left column) to body dimensions and hand/finger anthropometrics ($n = 39$)

Variable	BSA (m²)	SM ratio (m²/kg)	RFL	RFW (cm/kg)	BM (kg)
T_{min} (°C)	0.20	−0.18	0.10	−0.18	0.17
T_{max} (°C)	0.30	**−0.39**	0.30	**−0.37**	**0.35**
t_{onset} (min)	−0.07	0.19	−0.20	−0.01	−0.13
T_{mean} (°C)	0.20	**−0.32**	0.30	−0.21	0.25
T_{amp} (°C)	0.19	−0.30	0.25	−0.29	0.25
RIF	0.13	−0.19	0.27	−0.12	0.15
CIVDwave(#)	0.28	**−0.39**	0.28	−0.32	**−0.34**

Correlation coefficients (r) are provided for each variable. Bold indicates statistical significance ($p \leq 0.05$)

BSA body surface area, *SM* surface-to-mass ratio, *BM* body mass, *RFL* relative finger length, *RFW* relative finger width, and *RIF* Resistance index of frostbite

Table 2 Males and females CIVD parameters, body dimensions, perceptual measurements, and physiological responses for the subgroup of 7 males and 7 females ($N=14$; left side columns) and the entire sample ($N=39$; right side columns)

	Male ($n=7$)	Female ($n=7$)	p value	Male ($n=20$)	Female ($n=19$)	p value
CIVD parameters						
T_{mean} (°C)	8.0 ± 1.9	8.9 ± 1.6	$p=0.36$	8.6 ± 2.1	8.3 ± 2.2	$p=0.66$
T_{max} (°C)	11.2 ± 3.1	13.1 ± 1.2	$p=0.16$	12.2 ± 2.8	11.5 ± 2.8	$p=0.44$
T_{min} (°C)	5.9 ± 1.4	5.0 ± 1.7	$p=0.31$	5.8 ± 1.8	4.7 ± 1.2	$\mathbf{p=0.045}$
t_{onset} (min)	12.0 ± 4.4	9.6 ± 3.6	$p=0.28$	10.8 ± 3.5	10.4 ± 3.3	$p=0.71$
T_{amp} (°C)	5.4 ± 3.0	8.1 ± 2.1	$p=0.07$	6.4 ± 2.7	6.8 ± 2.8	$p=0.89$
RIF	7.4 ± 0.8	7.6 ± 1.0	$p=0.66$	10.4 ± 1.2	7.2 ± 1.1	$p=0.61$
$CIVD_{waves}$	1.2 ± 0.6	1.6 ± 0.7	$p=0.20$	1.4 + 0.6	1.4 + 0.6	$p=0.99$
Baseline (°C)	25.3 ± 2.6	25.1 ± 5.3	$p=0.92$	28.1 ± 4.9	25.1 ± 4.1	$\mathbf{p<0.002}$
Body dimensions						
Height (cm)	178.0 ± 3.1	177.0 ± 5.6	$p=0.69$	184.9 ± 7.3	171.0 ± 6.2	$\mathbf{p<0.001}$
Body mass (kg)	72.6 ± 9.2	72.1 ± 10.5	$p=0.92$	82.1 ± 12.3	66.3 ± 14.2	$\mathbf{p=0.001}$
Body surface area (m^2)	1.9 ± 0.1	1.9 ± 0.3	$p=0.86$	2.1 ± 0.2	1.8 ± 0.2	$\mathbf{p<0.001}$
Surface-to-mass ratio (m^2/kg)	0.03 ± 0.002	0.03 ± 0.002	$p=0.99$	0.025 ± 0.002	0.027 ± 0.003	$\mathbf{p=0.01}$
Relative finger length	0.04 ± 0.002	0.04 ± 0.002	$p=0.11$	0.04 ± 0.002	0.04 ± 0.002	$p=0.92$
Relative finger thickness (cm/kg)	0.03 ± 0.004	0.02 ± 0.005	$p=0.75$	0.02 ± 0.003	0.03 ± 0.006	$\mathbf{p=0.004}$
Perceptual						
$Pain_{hand}$	4.5 ± 2.1	4.1 ± 1.4	$p=0.70$	3.7 ± 1.8	5.4 ± 2.0	$\mathbf{p=0.03}$
TS_{hand}	−2.9 ± 0.9	−3.1 ± 0.6	$p=0.56$	−2.8 ± 0.7	−3.2 ± 0.6	$\mathbf{p=0.03}$
TC	2.1 ± 0.8	1.9 ± 1.2	$p=0.65$	1.9 ± 0.7	2.4 ± 0.9	$\mathbf{p=0.02}$
Physiological						
Avg heart rate (bpm)	67.3 ± 7.5	73.9 ± 13.0	$p=0.27$	68.7 ± 9.7	76 ± 9.4	$\mathbf{p=0.02}$
Avg core temperature (°C)	37.2 ± 0.2	37.3 ± 0.2	$p=0.41$	37.2 ± 0.3	37.3 ± 0.2	$p=0.37$

All values are the average of digits 2–5. Bold indicates significance set at $p \leq 0.05$

RIF resistance index for frostbite, *TS* thermal sensation, *TC* thermal comfort

and Tipton 2014). After pooling the data for both sexes ($N=39$), SM ratio showed a negative relationship with T_{mean} ($r=-0.32$, $p=0.045$), T_{max} ($r=-0.39$, $p=0.013$), and $CIVD_{waves}$ ($r=-0.39$, $p=0.022$); see Fig. 2. While we focused on the relation between CIVD parameters and body shape using ratios, Wickham and Cheung (2023) compared the CIVD response of a finger to the specific dimensions of that finger. Although the R^2 value was low in their study ($R^2=0.07$), Wickham and Cheung (2023) did find a significant, negative correlation to digit SM ratio during immersion (Wickham and Cheung 2023). Thus, the larger hands and thicker digits of males compared to females (Kulaksiz and Gozil 2002), contributing to smaller SM ratios, are related to increased blood flow and warmer fingers during cold stress. Additionally, modeling studies have shown that people with smaller and thinner hands and fingers experience colder skin temperatures (Kingma et al. 2023).

Large body masses alone produce and contain more body heat, leading to better CIVD responses, illustrated by the positive correlation between body mass and T_{max} ($r=0.35$) and $CIVD_{waves}$ ($r=0.34$). Although core temperature was the same between sexes, a larger body mass will have greater heat content, as heat content is the average mean body temperature multiplied by body mass. It is likely that the greater heat content will improve CIVD as there is more heat to be transported to the extremities. Additionally, CIVD is strongly influenced by the thermal state of the body. Individuals with a higher body core temperature have stronger CIVD responses (Daanen and Ducharme 1999; Takano and Kotani 1989), whereas those who have a lower core temperature have weakened CIVD (Daanen et al. 1997).

When not controlling for anthropometrics, females experienced stronger sympathetic responses, demonstrated by higher heart rates, more pain, colder thermal sensations, and worse thermal comfort during cold-water finger immersion, which is in line with the existing literature (Hohenauer et al. 2022). However, these differences were absent once anthropometrics were identical between sexes, highlighting that within our sample, only the smaller females experienced enhanced perceptual measurements, while the females with body and hand sizes like males did not have such elevated sympathetic responses. Related to CIVD parameters, we examined finger skin temperature prior to immersion of the hand and found that, for the entire sample, male finger skin temperatures at baseline were 3 °C higher than females (Males: 28.1 ± 4.9 °C, Females: 25.1 ± 4.1 °C, $p < 0.002$), stressing that 35 °C hand pre-immersion is necessary to eliminate baseline sex differences. In agreement, Jay and Havenith (2004) found that on average, male finger skin temperature while sitting in a thermoneutral room was 1.1 °C higher than females (Jay and Havenith 2004). The lower finger skin temperature in females may have been due to the increased vasoconstrictive tone in females resulting in lower finger and hand blood flow than males (Cooke et al. 1990; Daanen 2003), thus providing a lower heat input (Bollinger and Schlumpf 1976). Again, the baseline finger skin temperature differences were eliminated once anthropometrics were matched. Nevertheless, baseline finger temperatures have shown a negative correlation to the rate of finger cooling during cold-air exposure (Enander 1982). Therefore, differences in baseline finger skin temperature could affect the CIVD response during immersion.

When evaluating all 39 participants, there were no differences in any CIVD parameters, except for males having slightly higher T_{min} during immersion compared to females. Hormonal factors might also explain differences found in skin temperature of males and females for T_{min} and prior to immersion as males have less estrogen and progesterone than females, regardless of the menstrual cycle stage (Lauretta et al. 2018). Estrogens increase vasoconstriction, possibly by stimulating endothelial nitric oxide synthesis (Arora et al. 1998), up-regulation of vasoconstrictive alpha2-adrenoreceptors (Cankar and Finderle 2003), antioxidant properties (Yagi and Komura 1986), stimulation of prostacyclin, direct influence on the vascular wall, inhibition of prostanoids, and alteration of calcium flux in vascular smooth muscle (Arora et al. 1998). However, to effectively isolate sex as a variable, the matching of participants based on anthropometric measurements showed no sex differences in CIVD and perceptual responses, highlighting the importance of considering body composition in future CIVD investigations.

While this study provides valuable insights into factors impacting CIVD, several limitations should be considered. First, hormones have been shown to impact thermoregulation (Cicinelli et al. 1996; Nagashima 2015). In the current investigation, 11 females were in the luteal phase, 4 females were in the follicular phase, and the phases of the remaining 4 females were unknown. The uneven distribution is representative of the population as the luteal phase is longer than the follicular phase, allowing for a higher probability that most females would be in the follicular phase at any given time. Although menstrual cycle was not controlled for, there were no differences between menstrual phases for core temperature or any CIVD responses. Our sample may have been too small or biased based on menstrual phase. Sugawara et al. (2004), however, did observe a more pronounced CIVD response of females in the luteal phase compared to the follicular phase in 24 females. To separate the effects of sex from hand anthropometrics, we created a subgroup of males and females with identical anthropometrics; however, there were only 7 males and 7 females that could be matched. Selecting subsets reduces the statistical power. Future work should therefore consider recruiting a larger sample size of males and females with similar body and hand dimensions to improve the generalizability of findings to broader populations. Additionally, we did not measure the thickness of the subcutaneous layer of the skin of each finger or subcutaneous fat of the body. The variability in tissue skin properties may play a role in peripheral responses to cold.

In conclusion, a smaller SM ratio resulted in stronger CIVD responses, but relative finger length or finger width had no impact on CIVD responses, apart from thicker fingers displaying lower T_{max} values. Furthermore, when controlling for anthropometric measurements, sex had no effect on CIVD when anthropometry between sexes was similar. It appears that surface-to-mass ratio plays a larger role in CIVD responses compared to sex as the sole contributor. Understanding these responses is crucial for tailoring interventions and preventive measures, especially in occupational and recreational settings where exposure to cold environments is a concern.

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Author contributions RW and HD conceived and designed research. JG, RA, and RW conducted experiments. HD and RW analyzed data. HD provided subject matter expertise when writing the manuscript. DJ reviewed the manuscript and provided critical feedback. RW and HD wrote the manuscript. All authors read and approved the manuscript.

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Declarations

Conflict of interest The authors report there are no competing interests to declare.

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