Evaluating physiological strain during cold exposure using a new cold strain index

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Moran, Daniel S., John W. Castellani, Catherine O'Brien, Andrew J. Young, and Kent B. Pandolf. Evaluating physiological strain during cold exposure using a new cold strain index. Am. J. Physiol. 277 (Regulatory Integrative Comp. Physiol. 46): R556–R564, 1999.—A cold strain index (CSI) based on core (Tcore) and mean skin temperatures (Tsk) and capable of indicating cold strain in real time and analyzing existing databases has been developed. This index rates cold strain on a universal scale of 0–10 and is as follows: CSI = 6.67(Tcore – Tcore0)·(35 – Tcore0)−1 + 3.33(Tsk – Tsk0)·(20 – Tsk0)−1, where Tcore0 and Tsk0 are initial measurements and Tcore and Tsk are simultaneous measurements taken at any time t; when Tcore > Tcore0, then Tcore – Tcore0 = 0. CSI was applied to three databases. The first database was obtained from nine men exposed to cold air (7°C, 40% relative humidity) for 120 min during euhydration and two hypohydrations conditions achieved by exercise-heat stress-induced sweating or by ingestion of diuretics 12 h before cold exposure. The second database was from eight men exposed to cold air (10°C) immediately on completion of 61 days of strenuous outdoor military training, 48 h later, and after 109 days. The third database was from eight men repeatedly immersed in 20°C water three times in 1 day and during control immersions. CSI significantly differentiated (P < 0.01) between the trials and individually categorized the strain of the subject for two of these three databases. This index has the potential to be widely accepted and used universally.

hypothemic environments; indexes; rectal temperature; skin temperature

HYPOTHERMIA IS DIAGNOSED when core temperature (Tcore) declines to 35°C or below (18). It is a life-threatening situation, usually resulting from exposure to either a cold outdoor climate or immersion in cold water (12). Certain Tcore ranges have been used to categorize different stages of hypothermia and to evaluate the physiological limit humans can tolerate. Pozos et al. (18) defined the signs and the severity of hypothermia (mild, moderate, and profound) by Tcore.

Tcore as indicated by rectal temperature (Tre) may have been generally accepted as an appropriate physiological measure in the assessment of cold strain (9), although recent studies (16) have used the more rapidly responding esophageal temperature (Te). However, Tcore is not always reduced during cold exposure.

(18). Unchanged or even elevated Tcore is often observed during the initial period of cold exposure (9, 28, 29). An increase in Tcore during the initial period of cold exposure is attributed to the sympathetic nervous system mediating peripheral vasoconstriction, which results in redistribution of blood away from the periphery toward the core concomitant with an increase in metabolic heat production (3).

The most commonly used criteria to evaluate the degree of cold stress are ambient temperature (Tair) and wind chill. As Tair decreases, the gradient favoring heat flux from the body to the environment increases. Wind increases heat loss from the body to the environment (26). In 1945, Siple and Passel (22) developed the wind chill index to evaluate the cooling power of the environment by integrating the effects of Tair and wind velocity to assess the convective cooling power. Wind chill index also provides a convenient relative index for comparison between various experimental protocols and field situations. However, Tair alone does not adequately reflect cold strain, and there are also reports published concerning the limitations of the wind chill index (26). Wind chill and Tair only quantify stress to the unprotected body surface area. Further, the wind chill index is only applicable at wind speeds exceeding 20 m/s, overestimates the cooling power for a naked person, and underestimates the cooling power for a clothed person (26). Some corrections were suggested to overcome these limitations. For example, Boutelier (2) suggested inclusion of globe temperature in the index.

In 1950, Scholander et al. (21) described the critical temperature (CT) for exposures in air as the threshold Tair below which energy metabolism increases above the resting level. In 1962, Rennie et al. (19) defined CT for cold-water immersion as the lowest water temperature that an inactive subject could tolerate without exhibiting an increase in O2. The utility of using CT in air or water to quantify individual resistance or tolerance to cold stress has been challenged (6, 23), and Toner and McArdle (25) discussed this issue and concluded that better indexes are required. In 1987, Bittel (1) suggested using heat debt developed during exposure to cold as an index to assess the extent of the cold adaptation of an individual. However, the complexity of calculating this index [e.g., dry heat exchanges by radiation and convection (R + C), metabolic rate, convective and evaporative heat loss by the respiratory tract, and heat loss by cutaneous perspiration] limits its utility for use to rate cold strain online.

Recently, Moran et al. (15) developed a physiological strain index (PSI) to evaluate heat stress. The PSI is a
simple index based on only $T_{re}$ and heart rate (HR). This index successfully evaluated the heat strain in men who were exposed to a variety of exercise intensities combined with different levels of hypohydration (14) and different combinations of metabolic rate, climate condition, and clothing (15).

The purpose of this study was to develop an analogous, simple PSI to be used in cold environments. This index should be able to differentiate between degrees of cold strain and capable of indicating cold strain in real time as well as able to analyze existing databases on a simple scale of 0–10.

**MATERIAL AND METHODS**

Three different databases obtained from men exposed to cold were used in this study. The first database, consisting of $T_{re}$ and HR responses measured during exposure to cold air, served to develop the new index (16). The second database, containing $T_{re}$ and HR measurements taken from an independent study (28), was used to further validate the new index during cold-air exposures. The third database, taken from another separate study (5), was used to evaluate the applicability of the developed index for men during cold-water immersion and to compare the new index with an independent assessment of cold strain.

Protocol I. Nine healthy young men participated in this study (16). The physical characteristics of the subjects were as follows (means ± SE): age 24 ± 2 yr, height 178 ± 2 cm, body wt 77 ± 4 kg, and maximum rate of O$_2$ consumption ($V_{O_2max}$) 55 ± 1 ml kg$^{-1}$·min$^{-1}$. Each subject, dressed in shorts, socks, and shoes, completed three experimental cold-air exposures. The three exposures were completed with the subjects at different levels of hydration [euhydration (Eu), hypertonic hypohydration (HH), and isotonic hypohydration (IH)]. All exposures were completed within 15 days, and subjects served as their own controls. Two methods of dehydration were employed to achieve 4–5% loss of baseline body weight. To induce HH, subjects exercised in the heat (13) on the day before the trial. After 3–4 h of mild-intensity exercise in the heat, which resulted in sweating, fluid replacement was restricted. To achieve IH, subjects ingested a diuretic on the day before the scheduled 120- or 240-min exposure time because subjects voluntarily withdrew or their $T_{re}$ reached 35.0°C, the medical safety limit.

Calculations. The PSI was calculated as suggested by Moran et al. (15) as follows

$$PSI = 5(T_{re} - T_{re0}) \cdot (39.5 - T_{re0})^{-1} + 5(HR - HR_0) \cdot (180 - HR_0)^{-1}$$

where $T_{re0}$ and $HR_0$ are the initial measurements, and $T_{re}$ and $HR$ are simultaneous measurements taken at any time.

The insulation index (I index) to evaluate core-to-skin heat transfer was calculated in °C·W$^{-1}$·m$^{-2}$ as (27)

$$I = (T_{re} - T_{sk}) \cdot M^{-1} \cdot A_0^{-1}$$

where $M$ is the metabolic rate (in W) and $A_0$ is the body surface area (in m²).

The new cold strain index (CSI) developed in this paper (discussed in detail in RESULTS and DISCUSSION) was calculated as follows

$$CSI = 6.67(T_{core} - T_{core0}) \cdot (35 - T_{core0})^{-1} + 3.33(T_{skt} - T_{sk0}) \cdot (20 - T_{sk0})^{-1}$$

where $T_{core0}$ and $T_{sk0}$ are the initial measurements and $T_{core}$ and $T_{skt}$ are simultaneous measurements taken at any time; when $T_{core} > T_{core0}$ then $T_{core} - T_{core0} = 0$.

Protocol II. This study (28) examined the way in which chronic exertional fatigue and sleep deprivation, coupled with negative energy balance, affected thermoregulation during cold exposure. Eight healthy young men (age 28 ± 2 yr) with body weights of 67 ± 2, 74 ± 2, or 80 ± 2 kg (1st, 2nd, and 3rd trials, respectively) who were dressed in cotton athletic shorts and socks were exposed three times to 4 h of cold air (10°C). The first trial immediately followed completion of 61 days of strenuous outdoor military training (A), the second was after a short recovery of 48 h (SR), and the third trial was after long recovery of 109 days (LR). All three trials were conducted at the same time of the day and were in accordance with the same test protocol (28).

Protocol III. This study (5) examined whether serial cold-water immersions during one day would lead to a blunted response of the thermoregulation system. Eight healthy men (age 24 ± 4 yr, height 178 ± 3 cm, body wt 79 ± 3 kg, and $V_{O_2max}$ 50 ± 2 ml·kg$^{-1}$·min$^{-1}$) dressed only in shorts were immersed into cold water (20°C) for 120 min three times (0700, 1100, 1500) during one day (“repeat” group). About 3–4 wk before the experiments, control exposures, in which only a single immersion was employed on one day, were conducted at the same starting times as the three trials during repeat. However, the control trials were performed randomly during different weeks. All cold-water immersion trials employed the same test protocol.

Measurements. The $T_{re}$ was measured from a thermistor inserted 10 cm past the anal sphincter. In the first protocol, $T_{re}$ was measured by a thermocouple in a catheter placed at heart level. Skin temperature was measured at nine (protocols I and III) or five (protocol II) skin surface sites, and mean weighted skin temperature ($T_{sk}$) was calculated according to Gagge and Gonzalez (7). Mean body temperature ($T_{b}$) was calculated as 0.67·$T_{re}$ + 0.33·$T_{sk}$. In these three protocols, HR was measured from an electrocardiogram obtained from three chest electrodes and radiotelemetered to an oscilloscope-cardiotachometer. In protocol III, metabolic heat production was estimated from O$_2$ uptake and respiratory exchange ratio (7). Cumulative body heat debt was expressed as a positive number and was defined as the total negative storage integrated over time. Perception of thermal sensation was rated by using a category rating scale (30). A number of the experiments during the three protocols had to be terminated before the scheduled 120- or 240-min exposure time because subjects voluntarily withdrew or their $T_{re}$ reached 35.0°C, the medical safety limit.

The new cold strain index (CSI) developed in this paper (discussed in detail in RESULTS and DISCUSSION) was calculated as follows

$$CSI = 6.67(T_{core} - T_{core0}) \cdot (35 - T_{core0})^{-1} + 3.33(T_{skt} - T_{sk0}) \cdot (20 - T_{sk0})^{-1}$$

where $T_{core0}$ and $T_{sk0}$ are the initial measurements and $T_{core}$ and $T_{skt}$ are simultaneous measurements taken at any time; when $T_{core} > T_{core0}$ then $T_{core} - T_{core0} = 0$.

Statistical analysis. Physiological responses for the different experimental exposures were analyzed with SAS version 6.12 software with the use of the general linear models (GLM) procedure (extension of ANOVA) for univariate repeated measurements analysis. Linear models for HR, $T_{re}$, $T_{sk}$, and $T_{sk}$ as dependent variables were fitted by the least squares method (regression procedure), using each group at the different experimental exposure and subject designation as the independent variables. Multiple comparisons were controlled by using Tukey-Kramer tests. For protocol III, a two-way repeated-measures ANOVA was utilized to determine whether significant differences existed between the appropriate control condition and the repeat trial at the same time of day. Significant F ratios were analyzed post hoc by...
RESULTS

Database I. Generally, the physiological parameter exhibiting the largest relative drop during cold-air exposure was \( T_{sk} \). The fall in \( T_{sk} \) was marked from immediately after the start of cold-air exposure throughout the end of the first hour; thereafter, the change was less pronounced. There were no significant differences (\( P > 0.05 \)) in \( T_{sk} \) responses among the trials. The \( T_e \) increased during the initial period (~30 min) of the trials (\( P < 0.05 \)) and then decreased through the end of the experimental exposures (\( P < 0.05 \)).

We applied the original PSI, which had been developed for assessing strain in heat-stress conditions and was based on \( T_{core} \) (\( T_{es} \) in this database) and HR, to the database obtained for the cold-air exposure (Fig. 1). As can be seen, HR dynamics were of limited value for describing the cold stress because the HR changes during cold exposure were small. Thus we decided to construct a new index to evaluate cold stress (CSI) by using the same basic concept of PSI. This index was calculated from only two parameters as follows

\[
CSI = \alpha a + \beta b
\]

where \( a \) and \( b \) are physiological parameters suitable to describe cold stress and \( \alpha \) and \( \beta \) are the constants of these parameters. Shivering response would likely be one of the parameters. However, shivering-response assessment involves measuring metabolic rate, which...
is difficult to do online (the main reason for it not being included).

Because $T_{sk}$ changes very quickly in response to cold environments and because $T_{core}$ ($T_{re}$ or $T_{es}$) reflects thermoregulatory strain, we decided that these two parameters should adequately depict the cold strain. Because of ethical constraints, it was assumed that the maximal acceptable fall of $T_{core}$ deviation from normothermia to hypothermia during exposure to a cold climate is 3°C (based on maximal change from 38 to 35°C). Also, the maximal allowable decrease of $T_{sk}$ is assumed to be 15°C (based on maximal change from 35 to 20°C).

To evaluate cold stress on a universal scale of 0–10 and achieve a sensitive assessment during transitions and steady-state exposures, we constructed an index that enabled us to calculate the physiological strain in the cold in real time at any time. Although this index is not based on the maximal possible fall values for $T_{core}$ and $T_{sk}$, the lowest $T_{core}$ value (35°C) corresponds to the Human Use Review Committee limits for human experimentation. The lowest $T_{sk}$ value (20°C) typically observed during experimental cold-air exposure was assigned to increase the relative weight of $T_{sk}$ and the sensitivity of the index in assessing cold stress. Thus the following normalized physiological cold stress index (CSI) is suggested

$$CSI = 6.67(T_{core} - T_{core0}) \cdot (35 - T_{core0})^{-1}$$

$$+ 3.33(T_{sk} - T_{sk0}) \cdot (20 - T_{sk0})^{-1}$$

It has been assumed in other reports (7, 25, 26) that $T_{sk}$ represents the temperature of the periphery or the
shell and, combined with $T_{\text{core}}$ (either $T_{\text{re}}$ or $T_{\text{es}}$), enables the calculation of $T_b$. The weighting constants for $T_{\text{sk}}$ and $T_{\text{core}}$ represent the fraction of the body's mass that makes up the peripheral shell and core, respectively (25). According to Burton and Bazett (4), the calculation of $T_b$ in the cold assigned different weights for $T_{\text{core}}$ and $T_{\text{sk}}$, using constants of 6.67 for $T_{\text{core}}$ and 3.33 for $T_{\text{sk}}$. Thus CSI was constructed by assuming the same weighting ratio as for $T_b$. The new index was scaled to a range of 0–10 within the limits of the following values: $35 \leq T_{\text{core}} \leq 38^\circ C$ and $20 \leq T_{\text{sk}} \leq 35^\circ C$. Simultaneous measurements of $T_{\text{re}}$ and $T_{\text{es}}$ in this study revealed similar but consistently higher values for $T_{\text{re}}$ of $\sim 0.1$–0.2$^\circ C$ ($P < 0.01$). Therefore, application of CSI from both $T_{\text{core}}$ measurements ($T_{\text{re}}$ and $T_{\text{es}}$) and $T_{\text{sk}}$ is meaningful.

Because these subjects were not a homogeneous group and cold exposure resulted in large individual differences in physiological responses, data were analyzed individually. Figure 2 depicts the data obtained from three different subjects exposed to the same cold-air conditions at the same hydration state (IH) as from O'Brien et al. (16) but at different cold-strain levels during these cold exposures. Little cold strain, rated by CSI as 2, was observed for the first subject (Fig. 2A); low-to-moderate strain, which gradually increased and after 120 min increased to 4.8, is presented for the second subject (Fig. 2B); and high cold strain, which almost linearly increased with exposure time and ended as 8.7, is seen for the third subject (Fig. 2C).

The I index and the suggested CSI were applied to the same database, collected in the cold-air environment (protocol I) obtained from $T_{\text{re}}$ and $T_{\text{sk}}$. Generally, the two indexes were inversely correlated ($r = -0.916, -0.965$, and $-0.980$ for Eu, IH, and HH trials, respectively) from the 30th minute of cold exposure to the end of the exposure (Fig. 3). However, the I index, which is based on $T_{\text{es}}$ and $T_{\text{sk}}$ in addition to metabolic rate, was significantly different only between the IH and HH trials ($P < 0.03$). On the other hand, CSI discriminated between the trials, with significant differences ($P < 0.05$) found between HH and IH, or HH and Eu trials.

Database II. The most common criteria to assess cold strain are the absolute values of $T_{\text{re}}$ and $T_b$ or the changes in these temperatures during time of exposure ($\Delta T_{\text{re}}$ or $\Delta T_b$). The $T_b$ values, calculated from the $T_{\text{re}}$ and $T_{\text{sk}}$ of eight subjects exposed to the same 4 h of cold air after different recovery periods from long strenuous military training, are presented in Fig. 4. No significant differences in $T_b$ were found between the three trials during the first 120 min of the exposure and during the 240 min between A and LR. However, significant differences in $T_b$ were found between A and SR or LR at 150 and 180 min ($P < 0.05$; Fig. 4, top). Analysis of $\Delta T_b$ during the three trials revealed no significant difference between A and SR trials. A smaller change was found in LR that was significantly different from A and SR after 150 min, through the end of the exposure (Fig. 4, middle). The cold-strain assessment of the three trials by CSI is presented in Fig. 4 (bottom). Generally, the LR trial was assessed with significantly lower values during the 240-min exposure than the SR and A trials ($P < 0.01$). The A trial had the highest values ($P < 0.05$); however, no significant differences were found between A and SR during the second hour (60–120 min) of the exposures.

Database III. Cold-water immersion causes greater physiological strain than exposure to air at a similar temperature. In Fig. 5, CSI was applied to $T_{\text{re}}$ and $T_{\text{sk}}$ measured in eight men during the six experimental cold-water exposures (5). There were no $T_{\text{sk}}$ differences between control and repeat trials. Differences in $T_{\text{re}}$ between the control and the matched repeat trials did not achieve significance until the very end of immersion.
(120 min) and then only in the 1100 trial (P < 0.05). However, CSI values for repeat immersion exposures at 1100 and 1500 after 80 min through the end of these exposures were higher in comparison with the matched control exposures (Fig. 5, right). Despite these insignificant differences, the CSI differentiated between the repeat trials, assessed with absolute higher strain, and the control trials, demonstrating habituation of the thermoregulatory system by the higher strain assessment.

To further evaluate CSI, analysis was done between CSI and independent measurements of the cold strain by cumulative heat debt, thermal sensation assessment, and measurement of metabolic heat production. In general, heat debt correlated closely with CSI in the 0700, 1100, and 1500 trials (r = 0.989, 0.985, and 0.988, respectively; Fig. 6). The heat debt was higher in repeat rather than control in all three trials. However, at the end of the 1100 and 1500 trials (after 120 min), heat debt and CSI were significantly higher (P < 0.05) for repeat than control (Fig. 6, middle and bottom).

Comparisons between rated thermal sensation and CSI revealed high inverse correlations during the 0700, 1100, and 1500 trials (r = −0.973, −0.977, and −0.967, respectively; Fig. 7). The lower absolute numbers for thermal sensation rated by the subjects correspond to more pronounced sensation of cold. During the 1100 and 1500 trials, the control was assessed with lower strain by both thermal sensation and CSI than the repeat. However, thermal sensation exhibited a more pronounced difference between trials during the first 100 min, whereas CSI discrimination was greater at the end of the exposure time (100–120 min).

Fig. 6. Heat debt vs. CSI (means ± SE) obtained from 8 subjects at 0700 (top), 1100 (middle), and 1500 (bottom) for control and repeat experiments during cold-water (20°C) immersion (see Ref. 5).

Fig. 7. Rated thermal sensation vs. CSI (means ± SE) obtained from 8 subjects at 0700 (top), 1100 (middle), and 1500 (bottom) for control and repeat experiments during cold-water (20°C) immersion (see Ref. 5). Subjects rated their perception of thermal sensation using a numerical scale; lower numbers correspond to more pronounced sensation of cold.
The shivering response represented by metabolic heat production vs. CSI is depicted in Fig. 8. A very high correlation during the 0700, 1100, and 1500 trials ($r = 0.991$, 0.984, and 0.983, respectively) was found between these two variables in both experimental groups. However, in the 1100 and 1500 trials, the repeat exposure was assessed with higher CSI and lower metabolic heat production than control.

**DISCUSSION**

The most important new finding from this study is that core and skin temperature measurements can be integrated into a useful new index of cold strain. The CSI, for the three different databases under investigation (5, 16, 28), successfully evaluated the degree of cold strain for men at different levels of hydration status, at different recovery periods from long strenuous outdoor military training, and at different fatigue stages of the thermoregulatory system. This simple-to-use index is based on only two physiological parameters: $T_{re}$ (or $T_{es}$) and $T_{sk}$, which adequately depict the overall strain reflected by the body when exposed to cold environments. The CSI was applied to cold-air exposures and to cold-water immersion and found to assess quantitatively the cold strain on a universal scale of 0–10.

It is generally accepted that $T_{re}$ can describe physiological strain during cold exposures (18). However, $T_{re}$ is independent of environmental temperature over a wide range; therefore, the use of $T_{re}$ alone as an indication of thermal strain in the cold is of questionable value (9, 25). Minard (11) argued that changes in $T_{re}$ fail to reflect body heat loss during transient cooling. Greenleaf et al. (8) showed that $T_{re}$ declined slightly during the first 2 h of immersion in 34.5°C water; after 8 h, the $T_{re}$ values were higher than the initial $T_{re}$. In the present study, cold exposure produced cold strain, as indicated by vigorous shivering during cold-water immersion (5) and in cold air (16, 28), and yet, $T_{core}$ values often increased, especially during the start of an exposure to these cold environments. Thus $T_{re}$ alone is often an inadequate quantifier of cold strain. Furthermore, $T_b$ and $\Delta T_b$ were of limited value in assessing cold strain (Fig. 4) for the same reasons, because $T_{re}$ is the main determinator of $T_b$.

The $T_{sk}$, on the other hand, is rapidly affected by cold exposure. The skin is the barrier of the body interfacing with the ambient environment for heat-energy exchange by radiation, convection, and conduction. The skin, as stated by Porter and Gates (17), serves as “a transducer of the environment.” The $T_{sk}$ can change over a wider range (up to sevenfold more) than $T_{re}$. However, although $T_{sk}$ may reflect changes in ongoing dynamic heat exchange, $T_{sk}$ provides relatively little indication of the heat content or the temperature within the body; for that, $T_{core}$ can be assessed. Thus many investigators calculate $T_b$. We concluded that combining $T_{re}$ (or $T_{es}$), representative of the $T_{core}$, with $T_{sk}$, representative of the heat transfer between the body and the environment, would provide an index of cold strain.

The impact of water immersion on heat-balance mechanisms is greater than that of a similar air temperature because conductivity of water is 25 times greater than that in air (19) and because heat loss in water is particularly sensitive to the skin-water temperature difference. As a consequence, temperature gradients become great, and physiological responses are dramatic (24). Thus, to further the appreciation of the versatility of the CSI, we examined the cold strain from databases obtained from both cold-air and cold-water immersion.

The three indexes (PSI, I index, and CSI) were applied to the first database obtained from cold air (16). The application of the PSI on these data resulted in low positive and negative values across all the trials (Fig. 1). PSI was limited in its ability to evaluate cold stress because of three reasons. First, PSI was originally constructed to evaluate heat stress. As a consequence, it assumes maximal physiological values relevant for heat exposure rather than cold exposure. Second, PSI is

![Fig. 8. Metabolic heat production vs. CSI (means ± SE) obtained from 8 subjects at 0700 (top), 1100 (middle), and 1500 (bottom) for control and repeat experiments during cold-water (20°C) immersion (see Ref. 5).]
based on $T_{re}$ and HR. However, HR is mainly affected by exercise intensity, whereas, in these cold studies, the subjects were seated at rest, resulting in a relatively small change in HR dynamics during the trials (Fig. 1). In addition, an imbalance between the parasympathetic and the sympathetic nervous systems during cold exposure causes a large variability in HR (10). Third, the PSI lacks any factors reflecting the heat exchange between the environment and the body.

The I index, based on $T_{es}$, $T_{sk}$, and metabolic heat production, successfully discriminated the cold strain during cold exposures at different hypohydration levels. However, to calculate this index, a third parameter, metabolic rate, must be measured. This third parameter is not needed to calculate the simpler CSI. Application of CSI to the same databases clearly evaluated the relative strain with a simple scale ranging from 0 to 10. The use of individual $T_{es}$ and $T_{sk}$ values for assessment of cold strain revealed that Eu had the lowest strain. However, CSI, which combined these two parameters, rated the HH with the lowest strain. The latter is explained by the smaller change in $T_{es}$ during the 120-min exposure in the HH trials. The CSI effectively discriminated among cold strain at the different hypohydration levels, at different recovery periods from long outdoor strenuous training, and at different fatigue stages; it was found to be valid for both exposure in cold air and immersion in cold water.

The $T_{es}$ values are generally lower than the corresponding $T_{re}$ values (19). The latter values were also found in the cold-air database analyzed in this study (16). However, application of CSI to this database containing $T_{re}$ (CSI$_{Tre}$) or $T_{es}$ (CSI$_{Tes}$) and $T_{sk}$ measurements revealed no significant differences between CSI$_{Tre}$ and CSI$_{Tes}$ for each of the three trials ($P > 0.05$). The magnitude of this difference suggests that CSI, based on either $T_{es}$ or $T_{re}$, can provide meaningful values for the assessment of cold stress.

Evaluations of different cold strains by either the I index or heat debt and metabolic heat production were all found meaningful. However, the high correlation found between these assessments and the CSI strengthens the ability of CSI to serve as a simple tool constructed only from two parameters ($T_{core}$ and $T_{sk}$) for assessment of cold strain. Furthermore, rated thermal sensation during cold exposure as an independent method was found to be highly correlated with CSI.

The ability of an individual to be protected from cold climates and to avoid cold strain can be enhanced by proper clothing (25, 26). An appropriate clothing configuration considering insulation and water permeability can protect an individual from a hostile cold environment. The clothing used during cold exposure establishes a microenvironment at the skin surface and between the skin and the inner side of the clothing that is insulative in effect (26). However, all three databases used in this study had subjects dressed in only shorts or shorts, socks, and shoes. Thus, to apply CSI to different types of clothing, more studies should be conducted for proper validation.

In conclusion, the newly developed index is a complement to the existing literature regarding evaluation and assessment of cold strain. Although CSI might not provide as detailed a description of cold strain as heat debt calculation (1) or CT (26), it is significantly easier to calculate online. Thus CSI may be a useful tool, especially during online data acquisition and when metabolic rate measurements are not available. The CSI may also be useful for explaining discrepancies in experimental findings obtained by different investigators using various ambient conditions by providing a common reference point. This index has the potential to be widely accepted and to serve universally. However, further investigation is required to possibly adjust the CSI for a wider range of cold air and water temperatures and to consider exercise effects.

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