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Title Page

Title: Hybrid cooling vest for cooling between exercise bouts in the heat: effects and practical considerations

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Hybrid cooling vest for cooling between exercise bouts in the heat: effects and practical considerations

Abstract

While continuous cooling strategies may induce some ergonomic problems to occupational workers, cooling between work bouts may be an alternative for cooling them down in hot environments. The purpose of this study was to assess if wearing a newly designed hybrid cooling vest (HCV) between two bouts of exercise improved subsequent exercise performance. Inside a climatic chamber set at an air temperature of 37 °C and a relative humidity of 60%, twelve male participants underwent two bouts of intermittent exercise interspersed with a 30 min between-bout recovery session during which HCV or a passive rest without any cooling (PAS) was administered. Thermoregulatory, physiological, and perceptual strains were significantly lower in HCV than those in PAS during the recovery session ($p \leq 0.022$), which were accompanied with a large effect of cooling (Cohen's d=0.84~2.11). For the second exercise bout, the exercise time following HCV (22.13±12.27 min) was significantly longer than that following PAS (11.04±3.40 min, p=0.005, d=1.23) During this period, core temperature T_c was significantly lower by 0.14±0.0.15 °C in HCV than that in PAS. The heart rate drift over time was declined by 2±2 $bpm \cdot min^{-1}$ (p=0.001, d=1.00) and the rise in physiological strain index was reduced by 0.11±0.12 $unit \cdot min^{-1}$ (p=0.010, d=0.96) following the use of HCV. These findings suggested that using HCV could accelerate between-bout recovery and improve subsequent exercise performance by the enlarged body core temperature margin and blunted cardiovascular drift.

Keywords: intermittent cooling; temperature margin; heart rate drift; temperature gradient.

1 Introduction

In summer, many occupational groups such as sportsmen and construction workers usually perform highly intense physical activities under prolonged exposures to hot and humid environment. The combination of strenuous activities and high environmental temperatures may create excessive heat stress that ultimately imposes physiological and perceptual strains on the human body (Sawka et al., 2003), which in turn causes detrimental effects on physical performance (Quod et al., 2006). A broad range of cooling protocols has been reported in the literature on human thermoregulation during physical activities, in which the relationship between body cooling and physical performance has received considerable attention (Marino, 2002; Tyler et al., 2015; Bongers et al., 2015). Nevertheless, an optimal cooling protocol is yet to be identified for various occupational settings regarding remarkable differences in cooling strategies, cooling modalities, cooling duration, and work nature.

Cooling strategies may involve cooling before exercise (pre-exercise cooling) to expand body heat storage capacity (Quod et al., 2006), cooling during exercise (continuous cooling) to facilitate efficient heat loss and attenuate the increase in heat strain (Bongers et al., 2015), or cooling after exercise (post-exercise cooling) to minimize fatigue and hasten recovery (Brade et al., 2010). The literature reviews suggested that pre-exercise cooling would be helpful to improve exercise performance when the cooling duration reached up to 30 min (Marino, 2002). This cooling strategy seems impractical for many occupational groups. Continuous cooling has a large potential to improve exercise performance in hot environments (Tyler et al., 2015; Bongers et al., 2015). However, some continuous cooling strategies may be associated with many ergonomic problems, such as extra weight and restricted movement, which probably offset physiological cooling power (Constable et al., 1994). These practicality problems may account for the lack of interests of practitioners to date toward continuous cooling (Tyler et al., 2015).

In view of the nature of many activities, a small time frame (e.g., less than 30 min) is available between successive work bouts (e.g., Construction Industry Council, 2013). When working in hot environments in occupational settings where work-and-rest cycles are allowed, cooling between work bouts may be practical and efficient for cooling down workers and maintaining ensuing work performance. Cooling between these work bouts (i.e., intermittent cooling) has been reported beneficial for subsequent work or exercise performance associated with reduced thermoregulatory and physiological strains (Constable et al., 1994; Yeargin et al., 2006).

Different cooling modalities have been reported for intermittent cooling. Whole- or part-body immersion in cold water is frequently reported to be the optimal cooling stimulus (Hausswirth et al., 2012; Yeargin et al., 2006); however, the feasibility of cooling a large group of individuals such as occupational workers through this approach during short breaks has been questioned (Barwood et al., 2009). Other cooling modalities have been employed between repeated bouts of aerobic exercise, such as ice-slush beverage (Stanley et al., 2010), ice towel (DeMartini et al., 2011), fan cooling (Mitchell et al., 2001), cooling garments (Duffield et al., 2003; Constable et al., 1994), or a combination of these methods (Minett et al., 2012a). Many studies, but not in all cases (Duffield et al., 2003), have found beneficial effects of these cooling modalities on physiological responses and aerobic exercise performance. Although these cooling modalities have been widely applied in sports events, training sessions, and firefighting activities, the actual scenario is different in the construction industry. Ergonomic and logistical problems have been found in the construction industry that wearing personal cooling vest throughout the work session is impractical for the workers performing daily task in summer (Chan et al., 2016a). Some cooling interventions are impractical in outdoor working sites wherein congested site conditions may preclude the installation of blowers, or when cold water is difficult to be stored or delivered on-site.

Using properly designed personal cooling vests for intermittent cooling may be a practical and efficient field method, by which workers can attempt to counter the negative effects of heat stress with minimal ergonomic problems during work breaks. For this reason, a hybrid cooling vest (HCV) was recently developed for construction workers by the authors' research team, with particular regard to the heat-moisture performance of fabrics and the cooling power of cooling sources. Whether such a new cooling system is effective as an intermittent cooling intervention during the obligatory rest period in improving subsequent performance is yet to be determined. Thus, the purpose of this study is to examine the effects of this newly devised HCV for cooling between two bouts of exercise and subsequent exercise performance in a hot and humid environment.

2 Materials and methods

2.1 Research design and procedure

With a within-subjects repeated measures experimental design, the participants completed two trials in a randomized and counterbalanced order. The testing trial was conducted inside a climatic chamber (LabTester, KSON Ltd., Taiwan) with a hot environment (an air temperature of 37 °C and a relative humidity of 60%). For each participant the two trials were scheduled at the same time of the day (± 50 min on each occasion) and separated by a week, thereby controlling for possible effects of diurnal variations (Grisham, 1988) and allowing adequate recovery between subsequent trials. Upon arrival, the participant was briefed on the experiment protocol and requested to indicate the basic demographic information, such as name, height, and age. Then the participant was given 3 ml of warm water (~37.00 °C) per kg body weight (Yaspelkis and Ivy, 1991). The testing trial consisted of six sessions (Figure 1). The participant entered the climatic chamber and rested in a seated position for 10 min of buffer time and 30 min of pre-exercise rest (R1). This heat acclimation session was arranged to obtain acute adaptive effects to the heat exposure (Armstrong and Maresh, 1991). Baseline core temperature (T_{c0}) and heart rate (HR_0) were recorded during this session. The participant then performed the first bout of exercise (EX1) until the exercise terminated. The exercise bout consisted of intermittent activity including walking and jogging on a motorized treadmill (h/p/cosmos pulsar, Germany). The rationale behind the exercise protocol was to simulate the intermittent activities that construction workers were subjected to because diverse construction work is essentially intermittent by nature (Rappaport et al., 2003). On the basis of work-to-exhaustion-then-take-a-rest principle (Yi and Chan, 2014), the exercise would be discontinued if 1) the participants completed the one-hour exercise bout; 2) the participants' core temperature reached 38.5 °C (Barwood et al., 2009); 3) their heart rate reached 95% of the age-predicted maximum heart rate (220-age); or 4) they reported volitional fatigue. Once the exercise was discontinued, participants had a 6 min active recovery (AR1) walking on the treadmill. Then a 30 min post-exercise recovery session (R2) was arranged, during which either HCV or a passive rest condition without any cooling (PAS) was applied. Under both conditions participants remained seated for the entire recovery session. Rehydration was provided in the first 5 min of this period with warm water (~37 °C), and the volume of water intake was recorded. This designated cooling duration is consistent with a 30 min obligatory rest period for construction workers during afternoon work session (Construction Industry Council, 2013). Upon the completion of recovery session, the performance test on exercise time was subsequently undertaken in the second bout of exercise (EX2) with a same exercise protocol, which stopped once any of termination criteria was fulfilled, followed by a 6 min active recovery (AR2).

2.2 Participants

Twelve male university students participated in the experiment. All the participants did not have known health problems and they were considered apparently healthy. They engaged in sports around three times per week and were considered physically active. Prior to their informed consent to participate in the study, the participants were briefed clearly about the procedure of the testing trial. Mean (SD) age, weight, height, and body surface area (A_{D}=0.007184 ×

Height(cm)$^{0.725}$× Weight(kg)$^{0.425}$; DuBois and DuBois, 1916) of participants were 22 (3) years, 61 (8) kg, 170 (5) cm, and 1.7 (0.1) m^2, respectively.

2.3 Hybrid cooling vest and work attire

Each participant wearing a standard construction work attire (including a short-sleeved shirt and a pair of long pants) underwent the entire testing trial for both HCV and PAS conditions. Details of this work attire have been published elsewhere (Chan et al., 2016b). HCV was worn over the work attire. The newly designed HCV (Figure 2) employs eight packs of phase change material (PCM, 120 cm^2 and 110 g per pack) (Climator, Sweden) for absorbing heat when they change from a solid to a liquid state. The melting point and latent heat of fusion of PCM is 28 °C and 128 J/g, respectively. Just before the beginning of recovery session in the HCV condition, PCMs were inserted into the mesh polymer pockets of the vest: four at the front side and four at the back side. Two small detachable electronic air fans are mounted on the lower back of the vest and blow on the torso, which are powered by one pack of the chargeable lithium polymer battery (7.4 V, 4400 mAh). Each fan produces an airflow rate of 20 L/s. The two-layer vest is composed of the upper layer of nylon fabric and breathable mesh lining. The cooling vest has a zipper on the front, allowing easy application and removal. Overall, the total mass of the cooling vest (including all auxiliaries) is 1.53 kg. All the ensembles that fit the body size of the participants were used. All clothing ensembles and their accessories (including PCMs) were stored at an air-conditioning temperature of 20 °C and a relative humidity of 40% outside the chamber.

2.4 Measurements and calculations

An ingestible sensor detecting core (intestinal) temperature (CorTemp, HQI, the U.S.A.) was calibrated to ensure its function and accuracy. The calibration procedure followed the study of Chan et al. (2016b). The participants were instructed to swallow the sensor with warm water at least 4 hours before their scheduled arrival, and to avoid cigarettes, or caffeinated products on the day before and the day of testing. Upon arrival at the laboratory, the participant was dressed with the work attire and equipped with a CorTemp data logger, skin thermistor sensors (LT8A, Gram Co., Japan), and heart rate chest belt with its wrist-based monitor (Polar Wearlink, the U.S.A.), for recording body core temperature (T_c), skin temperatures (T_{sk}), and heart rate (HR), respectively. Along with the measurement of physiological parameters during the testing trial, rating of perceived exertion (RPE) and thermal sensation (TS) were synchronously recorded every 3 minutes. The RPE adopts an 11-point scale from 0 = rest to 10 = extremely hard (Borg, 1998), and TS refers to a modified ASHRAE (2004) scale with anchors from 1 = cool to 7 = hot. WBGT was measured by a heat stress monitor (QUESTemp°36™, Australia) inside the chamber. Determined by the prescribed physiological or fatigue threshold, performance measurement on exercise time (min) was monitored by the treadmill.

Physiological and perceptual responses were recorded synchronously throughout the testing trial. Body temperatures (T_c and T_{sk}) and heart rate (HR) were sampled every 30 s. Skin temperatures were measured with a four-point method at skin surface of the chest (T_{chest}), forearm ($T_{forearm}$), thigh (T_{thigh}), and calf (T_{calf}). The mean skin temperature ($\overline{T_{sk}}$) and the mean body temperature ($\overline{T_b}$) was calculated according to Equations (1) (Ramanathan, 1964) and (2) (Colin et al., 1971), respectively. Thermal gradient between T_c and $\overline{T_{sk}}$ ($T_c - \overline{T_{sk}}$) (Lee and Haymes, 1995) was figured. The rate of heat storage was calculated in Equation (3) (Lee and Haymes, 1995).

$$\overline{T_{sk}} = 0.3\,(T_{chest} + T_{forearm}) + 0.2\,(T_{thigh} + T_{calf}) \tag{1}$$

$$\overline{T_b} = 0.8T_c + 0.2\overline{T_{sk}} \tag{2}$$

$$\dot{S} = C_b \times \frac{m}{A_D} \times \frac{\Delta\overline{T_b}}{t} \tag{3}$$

where $\dot{S}$ is the rate of heat storage in $kJ \cdot m^{-2} \cdot hr^{-1}$; $\Delta\overline{T_b}$ is the change in mean body temperature; C_b is the specific heat capacity of the body issue, named3.47 $kJ \cdot kg^{-1} \cdot {}^{o}C^{-1}$; m is the body mass in kg; A_D in m^{-2} is the body surface area; t is the time interval in hr.

The physiological strain index (PhSI) (Equation (4); Moran et al., 1998; Tikuisis et al., 2002) was calculated to assess the physiological strain induced by exercise-heat stress. The perceptual strain index (PeSI) was calculated according to Equation (5) (Tikuisis et al., 2002; Yang and Chan, 2015). The output of each index is scaled from 0 to 10 where 0 represents no strain and 10 extremely high strain.

$$PhSI = 5 \times \frac{T_{ci} - T_{c0}}{39.5 - T_{c0}} + 5 \times \frac{HR_i - HR_0}{HR_{max} - HR_0} \tag{4}$$

where T_{c0} and HR_0 are the initial core temperature and heart rate prior to the trial, respectively; T_{ci} and HR_i are simultaneous core temperature and heart rate during the testing trial, respectively; HR_{max} is maximum heart rate of the participant achieved during exercise, which is substituted into the equation if it exceeds 180 bpm.

$$\mathrm{PeSI} = 5 \times \frac{\mathrm{RPE_i}}{10} + 5 \times \frac{\mathrm{TS_i} - 1}{6} \qquad (5)$$

where RPE_i and TS_i are the perceived exertion and thermal sensation respectively, taken at any time during the testing trial.

2.5 Statistical analysis

A two-way (Condition × Bout) analysis of variance (ANOVA) with repeated measures was separately performed to compare differences in means of physiological (T_c, $\overline{\mathrm{T_{sk}}}$, HR, $T_c - \overline{\mathrm{T_{sk}}}$, $\dot{S}$ and PhSI) and perceptual data (PeSI), using repeated measures of condition (HCV and PAS conditions) and test bout (R1, EX1, AR1, R2, EX2, AR2). The Greenhouse–Geisser correction was designated as statistical significance when the Mauchly's Test of Sphericity was violated and the modified degrees of freedom are provided after the adjusted F value accordingly. Significant main and interaction effects were analyzed using paired-sample t-test with Bonferroni adjustments. Where any significance was detected, tests of simple main effect of condition at each test bout or time point were further performed. Paired-sample t-test was performed to compare the difference in the cooling rate ΔT_c (ºC·min^{-1}) during recovery session between conditions.

Due to the difference in exercise time in each exercise bout, changes in PhSI and PeSI over time were figured as ΔT_c, $\Delta\overline{\mathrm{T_{sk}}}$ (ºC·min^{-1}), ΔHR (bpm·min^{-1}), ΔPhSI and ΔPeSI ($\text{unit}\cdot\text{min}^{-1}$). Paired-sample t tests were employed to assess the differences of exercise time, ΔT_c, $\Delta\overline{T_{sk}}$, ΔHR, ΔPhSI, ΔPeSI, $\dot{S}$, and $T_c - \overline{T_{sk}}_{END}$ (i.e., at the end of each exercise bout) within participants between the PAS and HCV conditions. Pearson correlation analysis was used to examine the relationship between exercise time and the aforementioned parameters during EX2. The following criteria were adopted to interpret the magnitude of correlation (r) between test measures: <0.1, trivial; 0.1–0.3, small; 0.3–0.5, moderate; 0.5–0.7, large; 0.7–0.9, very large; 0.9–1, almost perfect (Hopkins et al., 2009).

All data were reported as mean value and standard deviation (SD). The significance level was set at $p<0.05$. Effect size analysis was also used to indicate small, moderate, or large cooling effect noted in the data between conditions. A Cohen's *d* of <0.20 is classified as a trivial effect, 0.20–0.49 as a small effect, 0.50–0.79 as a moderate effect and >0.80 as a large effect (Minett et al., 2012b). The *p* value and the *d* value were presented for the comparison of mean differences between HCV and PAS. 95% confidence interval (CI) of mean differences between HCV and PAS was also figured. Statistical analyses were performed using SPSS V.21.

3 Results

Results of a two-way (Condition × Bout) (ANOVA) with repeated measures revealed that T_c and $\dot{S}$ in HCV were significantly lower than those in PAS across the entire test (38.11±0.44 °C and 38.19±0.46 °C, p=0.024; 124.30 ±189.00 $\text{kJ}\cdot\text{kg}^{-1}\cdot{}^{\circ}\text{C}^{-1}$ and 147.71±179.62 $\text{kJ}\cdot\text{kg}^{-1}\cdot{}^{\circ}\text{C}^{-1}$, p=0.023), with a small effect of cooling (*d*=0.13~0.18). Each physiological and perceptual parameter remained similar between HCV and PAS conditions during both R1 and EX1 (Table 1, Figure 3). Compared with PAS during R2, T_c significantly decreased by 0.22±0.24 °C in HCV (95%CI: -0.38 to -0.07 °C), accompanied with a significant decline in $\overline{T_{sk}}$ by 0.97±0.47 °C (95%CI: -1.27 to -0.67 °C), $\dot{S}$ by 68.89±50.83 $kJ \cdot kg^{-1} \cdot {}^{o}C^{-1}$ (95%CI: -101.19 to -36.60 $kJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$), PhSI by 0.66±0.84 unit (95%CI: -1.20 to -0.12 unit), and PeSI by 2.29±0.88 unit (95%CI: -2.85 to -1.73 unit), as well as a noticeable enlarged thermal gradient $T_c - \overline{T_{sk}}$ by 0.75±0.56 °C (95%CI: 0.39 to 1.11 °C). The cooling rate in HCV (0.024±0.007 $^{\circ}C \cdot min^{-1}$) was significantly larger (p=0.004, 95%CI: 0.003 to 0.010 $^{\circ}C \cdot min^{-1}$) than that in PAS (0.017±0.006 $^{\circ}C \cdot min^{-1}$) with a strong effect of cooling (*d*=1.07).

As shown in Figure 4, EX1 resulted in non-statistically significant differences and trivial effect sizes for exercise time, ΔT_c, $\Delta\overline{T_{sk}}$, ΔHR, $T_c - \overline{T_{sk}}_{END}$, $\dot{S}$, ΔPhSI, and ΔPeSI between the HCV and PAS conditions (p=0.31~0.98, *d*=0.00~0.26). Among the twelve participants, ten and eleven stopped the exercise because they reached the prescribed threshold of core temperature in HCV and PAS, respectively. The remaining participants in each trial stopped as they approached the prescribed threshold of heart rate. For both conditions no voluntary exhaustion was reported in EX1. For both exercise bouts, no participants completed the one-hour testing trial.

For the second exercise bout, the exercise time following HCV and PAS was 22.13±12.27 min and 11.04±3.40 min, respectively (p=0.005; *d*=1.23, large effect). Their mean difference was 11.04±11.02 min (95%CI: 4.08 to 18.09 min), with the mean relative improvement of 99.5±89.5%. The number of participants stopping EX2 in HCV because they approached the prescribed threshold of core temperature, 95% of the age-predicted maximum heart rate, and volitional fatigue was 9, 2, and 1, respectively. Ten and two participants terminated the exercise in PAS because they reached the critical core temperature and heart rate, respectively.

Compared with PAS during EX2, there was a significant decrease in T_c by 0.14±0.15 °C in HCV (95%CI: -0.23 to -0.04 °C, Table 1). ΔHR was significantly reduced by 2±2 $bpm \cdot min^{-1}$ (95%CI: -3 to -1 $bpm \cdot min^{-1}$) in HCV (4±2 $bpm \cdot min^{-1}$) than in PAS (6±2 $bpm \cdot min^{-1}$, p=0.001; *d*=1.00, large effect). ΔPhSI was also significantly declined by 0.11±0.12 $unit \cdot min^{-1}$ (95%CI: -0.18 to -0.03 $unit \cdot min^{-1}$) in HCV (0.24±0.12 $bpm \cdot min^{-1}$) than in PAS (0.35±0.11 $bpm \cdot min^{-1}$, p=0.010; *d*=0.96, large effect). However, $\Delta \overline{T_{sk}}$ was significantly larger by 0.05±0.06 $°C \cdot min^{-1}$ (95%CI: 0.01 to 0.08 $°C \cdot min^{-1}$) in HCV (0.06±0.02 $°C \cdot min^{-1}$) compared with that in PAS (0.01±0.06 $°C \cdot min^{-1}$, p=0.026; *d*=1.1, large effect). Meanwhile, $T_c - \overline{T_{sk}}_{END}$ was significantly lower by 0.33±0.43 °C (95%CI: -0.61 to -0.06 °C) in HCV (1.94±0.58 °C) than that in PAS (2.27±0.79 °C, p=0.022; *d*=0.48, moderate effect). Although a trend for a larger $\dot{S}$ was noticeable in HCV (*d*=0.54), no significant differences were found between HCV and PAS (Table 1). Non-statistically significant difference and trivial cooling effect for ΔT_c and ΔPeSI were found between the HCV and PAS conditions (p=0.778~0.942, *d*=0.00~0.12).

For EX2, a large and significantly negative relationship between exercise time and ΔHR (r=-0.77, p<0.001) and ΔPhSI (r=-0.78, p<0.001) were observed. There was a significantly moderate negative relationship between exercise time and ΔT_c (r=-

0.63, p=0.001). A significantly small negative relationship between exercise time and ΔPeSI was also found (r=-0.42, p=0.040).

4 Discussion

This study was designed to examine the effectiveness of using a newly designed HCV as a cooling maneuver between exercise bouts to accelerate recovery and improve subsequent exercise performance in the heat. Compared with no intermittent cooling, the current findings indicated that using HCV between two exercise bouts (1) achieved a large cooling effect (*d*=0.84~2.11) with statistical significance (p≤0.022) in reducing body heat strain during the 30 min recovery session as a recovery cooling modality (Table 1, Figure 3), and (2) exhibited a mean relative improvement of 99.5±89.5% in exercise time during EX2 as a precooling maneuver (Figure 4).

4.1 Recovery cooling effects of HCV

The current findings revealed that using HCV between exercise bouts aided in accelerating recovery from exercise-induced heat stress and this was reflected by the reduced physiological and perceptual strains. When HCV was applied in a hot and humid environment, a superficial cooling effect removed the body heat from the skin surface and thus cooled the peripheral blood before returning to the core of the body to cool the core temperature (Yeargin et al., 2006; Cleary et al., 2014). This outcome is evidenced by the statistical significance and large cooling effect for lowering $\overline{T_{sk}}$ in HCV during R2 (p<0.001, *d*=1.60). Compared with that in PAS during R2, the lower $\overline{T_{sk}}$ in HCV accounted for the enlarged gradient temperature between the body core and the skin. Such a wider range of thermal gradient can facilitate heat loss by promoting internal heat conduction via blood from the body's core to the periphery (Pandolf et al., 1995). This result is evidenced by the statistical significance and large cooling effect for reducing core temperature in HCV (p=0.009, *d*=1.28). The reduced $\overline{T_{sk}}$ in HCV also accounted for the enlarged temperature gradient between skin surface and ambient environment that might further facilitate dry heat loss. Continuously decreased body temperatures accounted for the negative $\dot{S}$ during R2 in both conditions. Compared with PAS, HCV resulted in lower rate of heat storage probably because of the improved efficiency of conductive and convective heat dissipation evidenced by the larger core to skin temperature gradient. The beneficial thermoregulatory effect of HCV on reducing core temperature (i.e., 0.024 $°C \cdot min^{-1}$) was also at a significantly faster rate than that under PAS in the heat (0.017 $°C \cdot min^{-1}$) with a large cooling effect.

Lower values of core temperature and heart rate accounted for a smaller level of physiological strain. The lower level of physiological strain may further account for the less heat strain felt by the participants in HCV. Interestingly, the findings showed that participants might overestimate the strain level in PAS as the mean value of PeSI was slightly higher than that of PhSI. In contrast, participants might underestimate strain level in HCV, indicating that they were more pleasant over the concurrent physiological strain. This implied that wearing HCV could improve the comfort level of participants in the heat and possibly reduce fatigue. Nevertheless, the underestimated heat strain perception may be associated with a placebo effect of wearing HCV as the participants were not blinded to the cooling modality.

4.2 Precooling effects of HCV between exercise bouts

The benefits of using HCV between exercise bouts were evident for improving subsequent exercise performance, which were similar to the effects of precooling strategy (Hausswirth et al., 2012). The current findings indicated that the absolute value of core temperature was significantly lower during EX2 following precooling compared with that without, allowing a larger margin to increase core temperature and creating a greater sink for metabolic heat generated during exercise, and ultimately lengthening the time to reach the prescribed temperature threshold of 38.5 °C (Marino, 2002; Quod et al., 2006; Bongers et al., 2015). In addition to the decline in the absolute value of core temperature, the blunted rise in core temperature is also a major determinant factor for exercise performance after precooling (Marino, 2002). This is reinforced by the current finding of a moderate negative correlation between exercise performance and the rise in core temperature. However, using HCV between exercise bouts did not significantly result in slowing down the rise in core temperature during subsequent exercise, supporting the previous finding that precooling creates a larger heat storage capacity without changing the rate of heat gain (Webborn et al., 2005). The rise in PeSI remained similar during EX2 between conditions, as no external cooling was applied. Despite this, a small correlation between exercise time and the blunted rise in perceptual strain index was found, indicating that slower increase in perceptual strain may extend the exercise time to fatigue. However, this perceptual benefit for performance enhancement following cooling may be attributed to a placebo effect (Hornery et al., 2005).

The current findings indicated that exercise performance in HCV could be enhanced with the reduced heart rate drift over time and the blunted rise in physiological strain index. Evidences showed that cardiovascular drift is associated with elevation of core temperature and the exercise time to fatigue (Coyle and González-Alonso, 2001; Thompson, 2006). Without precooling, a higher T_c in PAS might be associated with smaller stroke volume and faster cardiovascular drift (Adams et al., 1992; Coyle and González-Alonso, 2001). With a faster upward heart rate drift in PAS, the maximum heart rate could be reached within a shorter exercise time whereupon cardiac output was comprised (Thompson, 2006). The successful manipulation of heart rate drift explained the slower rate of PhSI increase in HCV.

Of interest, a faster rewarming of $\overline{T_{sk}}$ in HCV was observed during EX2. This was also notable in the studies of Booth et al. (1997) and Kay et al. (1999); however, the underlying mechanism of precooling that elevate of skin temperature is yet to be determined. When participants transited from R2 with wearing HCV to EX2 without cooling, a superficial heating effect might occur, resulting in acute vasodilatation of local blood vessels and ultimately increasing skin temperatures. While skin temperature largely depends on the ambient environment (Brotherhood, 2008), it might quickly react to the heat with a possible acute heating effect. Despite a faster increased in $\overline{T_{sk}}$ accompanied with a reduced thermal gradient in HCV, the increase in T_c did not accelerate further. These findings suggested that the sufficiently declined core temperature in HCV may largely contribute to improving exercise performance, even with the increased skin temperature and decreased thermal gradient. Furthermore, the increased $\overline{T_{sk}}$ associated with an increase in skin blood flow did not occur together with faster heart rate drift in HCV, probably because blood flow from the central circulation to the peripheral veins was attenuated due to a lower core temperature (Montain and Coyle, 1992). The underlying mechanism of such an acute response of mean skin temperature and concurrent blunted heart rate drift remained unclear, which may be disclosed by further measurements on cutaneous blood flow and stoke volume.

The exercise time was found with no significant correlation with rate of heat storage in this study. This outcome reinforced previous findings that rate of heat storage may not be a primary factor to determine exercise performance, but by a core large temperature margin toward the critical temperature (Quod et al., 2008). Although no significant difference was found between conditions, a moderate effect for higher rate of heat storage during EX2 in HCV was found (*d*=0.54). Similar to previous studies on precooling maneuvers, the significantly larger heat storage rate was found during exercise after precooling than that their control conditions (Lee and Haymes, 1995; Booth et al., 1997; Kay et al., 1999). This is because precooling improves heat storage capacity to store metabolic heat load by exercising. However, the marked increase in skin temperature in HCV possibly lessoned the cooling effect to enlarge heat storage rate in the current study.

4.3 Practical considerations

The cooling effect on human thermoregulation and physical performance can vary under different environmental conditions, exercise intensities, cooling durations and cooling modalities (Barwood et al., 2009; Quod et al., 2006). The participants in this study experienced a stressful environmental condition with the recorded

WBGT value of 32.45 ± 0.36 °C. This condition simulated a similar hot environment in real construction work settings (Wong et al., 2014). Compared with the recorded mean value of heart rate of construction workers (i.e., 111±18 bpm) in Wong et al. (2014)'s field studies, the present heart rate data also lies around the upper limit of 95% of values (i.e., 147 bpm). This supports that the current exercise protocol may simulate the workload of construction workers in terms of the datasets of heart rate. A further challenge lies in the exercise mode used in the current protocol, in which the running exercise may not exactly present the actual manual work of construction workers (e.g., heavy lifting, forceful pulling). Despite this, treadmill-running exercise as a whole body mode is better for manipulation than the upper (arm ergometer) or lower body modes (cycling). Alternatively, the future field experiment can be performed in real-work settings regarding this concern. Moreover, the recruitment of young university students is another potential design limitation. Furthermore, the Hong Kong construction workers are recommended to have 15 min and 30 min rest periods in the morning and the afternoon, respectively, when working in hot weather (Construction Industry Council, 2013). In the present study it is remained unknown whether a shorter cooling duration (~15 min) would induce sufficient reduction in core temperature and further incur alterations in ensuing exercise performance.

Despite these limitations, the current study provided laboratory-based evidences that the new HCV can be considered for using during a brief break, as an alternative to using no cooling vest. First, using HCV during between exercise bouts may potentially reduce the risk of mild hyperthermia (~38.5 °C) with a faster reduction in core temperature. This cooling rate of this vest was slightly lower than that of the other reported personal cooling vests (i.e., 0.03－0.04 °C·min^{-1}) (Cleary et al., 2014; Brade et al., 2010; Lopez et al., 2008). Interestingly, these higher cooling rates did not result in a significant difference compared with those in the no-vest conditions. By contrast, the cooling rate of HCV was found both statistical significance and large effect as compared with no-vest condition in the current study. Apart from further investigations on different cooling modalities in a standardized cooling protocol, their practicalities in the construction industry should not be ignored. For the newly designed HCV, its PCMs can be easily stored in air-conditioned rooms (i.e., <28 °C), and the battery driving air fans are rechargeable. In this regard, construction workers are encouraged to consider the portable HCV as a cooling option in terms of its effectiveness and practicality. Alternatively, future studies on a combination of HCV with other feasible cooling modalities (e.g., cool water intake, and water-mist blowers) can be launched to identify the optimal cooling strategies.

5 Conclusions

The findings of this study indicate that wearing HCV between two bouts of exercise result in a remarkable reduction in thermoregulatory, physiological and perceptual strain during recovery session. Comparison between HCV and PAS recovery methods suggests that superficial cooling provided by HCV facilitated better efficiency of heat loss, as evidenced by lower body temperatures, larger thermal gradient, and lower heat storage rate. The benefit of HCV also lies in the alleviation of perceptual strain, implying that the wearers may experience heat strain relief and accelerate recovery from fatigue. Furthermore, compared with no intermittent cooling condition, HCV enhanced the ensuing exercise performance of participants by a mean relative improvement of 99.5±89.5% in exercise time. Such a noticeable benefit may be associated with the enlarged core temperature margin toward the critical temperature, accompanied with a slower heart rate drift and the blunted rise in physiological strain during exercise. Given the logistical arrangements at construction sites, the use of HCV may be an alternative cooling intervention that can aid workers accelerate recovery and enhance ensuing work performance; however, this should be validated by conducting field experiments in future.

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List of tables

Table 1 Results of a two-way (Condition × Bout) analysis of variance (ANOVA) with repeated measures (mean±SD)

List of figures

Figure 1 Intermittent exercise and testing trial

intermittent running and walking were repeated until the prescribed threshold was reached. Hybrid cooling vest (HCV) or a passive rest without any cooling (PAS) was applied during between-bout recovery (R2).

Note: The number on the red bar represents the speed in km/h, whereas that on the blue bar represents the slope in percentage (%).

R1 – Pre-exercise rest, EX1 – First bout of exercise, AR1 – Active recovery following the first exercise bout, R2 – Between-bout recovery, EX2 – Second bout of exercise, AR2 – Active recovery following the second exercise bout.

Figure 2 The newly designed hybrid cooling vest when the two air fans were turned on

Figure 3 Physiological and perceptual responses between the HCV and PAS conditions: (a) core temperature, (b) mean skin temperature, (c) thermal gradient, (d) rate of heat storage, (e) heart rate, (f) physiological strain index, (g) perceptual strain index

Note: Error bar presents standard deviation.

* denotes significant difference between conditions

Figure 4 Exercise performance, physiological and perceptual responses between the HCV and PAS conditions at the end of the two bouts of exercise

Note: Error bar presents 95% confidence interval.

* denotes significant difference between conditions

Table 1 Results of a two-way (Condition × Bout) analysis of variance (ANOVA) with repeated measures (mean±SD)

Test bout	**Condition**	T_c (°C)*	$\overline{T_{sk}}$ (°C)	T_c-$\overline{T_{sk}}$ (°C)	$\dot{S}$ (kJ·m^{-2}·hr^{-1}) *	HR (bpm)	PhSI (unit)	PeSI (unit)
R1	HCV	37.34 (0.14)	35.63 (0.33)	1.66 (0.35)	68.76 (27.22)	79 (6)	0.63 (0.18)	3.99 (0.78)
	PAS	37.36 (0.14)	35.52 (0.47)	1.89 (0.51)	57.60 (64.32)	80 (9)	0.61 (0.15)	3.91 (0.81)
	95% CI of mean differences between HCV and PAS	-0.14, 0.10	-0.16, 0.38	-0.51, 0.05	-29.04, 51.36	-6.65, 6.22	-0.14, 0.19	-0.25, 0.41
EX1	HCV	37.89 (0.11)	36.15 (0.26)	1.74 (0.31)	214.48 (47.96)	148 (12)	4.94 (0.50)	6.17 (1.30)
	PAS	37.89 (0.12)	36.03 (0.49)	1.86 (0.52)	231.84 (81.09)	146 (13)	4.75 (0.35)	6.15 (0.96)
	95% CI of mean differences between HCV and PAS	-0.08, 0.08	-0.11, 0.35	-0.38, 0.15	-57.91, 23.19	-8.67, 11.89	-0.23, 0.55	-0.49, 0.51
AR1	HCV	38.56 (0.13)	36.63 (0.39)	1.94 (0.37)	168.20 (174.58)	146 (10)	6.43 (0.61)	5.63 (1.25)
	PAS	38.58 (0.09)	36.46 (0.57)	2.13 (0.54)	209.20 (114.58)	146 (14)	6.37 (0.60)	5.89 (1.15)
	95% CI of mean differences between HCV and PAS	-0.11, 0.07	-0.07, 0.41	-0.46, 0.07	-145.53, 63.52	-8.19, 9.72	-0.40, 0.48	-1.12, 0.59
R2	HCV	38.16 (0.18) †	35.64 (0.64) †	2.52 (0.56) †	-199.07 (67.06) †	109 (13)	3.79 (0.86) †	2.64 (0.91) †
	PAS	38.39 (0.18)	36.61 (0.57)	1.77 (0.53)	-130.18 (54.95)	114 (14)	4.45 (0.70)	4.93 (1.24)
		p=0.009, *d*=1.28	**p<0.001, *d*=1.60**	**p=0.001, *d*=1.38**	**p=0.001, *d*=1.12**		**p=0.022, *d*=0.84**	**p<0.001, *d*=2.11**
	95% CI of mean differences between HCV and PAS	**-0.38, -0.07**	**-1.27, -0.67**	**0.39, 1.11**	**-101.19, -36.60**	-12.62, 1.52	**-1.20, -0.21**	**-2.85, -1.73**
EX2	HCV	38.13 (0.09) †	36.01 (0.56)	2.12 (0.55) †	286.39 (115.89)	155 (10)	5.78 (0.43)	5.93 (1.50)
	PAS	38.27 (0.10)	35.85 (0.79)	2.41 (0.76)	212.42 (155.24)	154 (13)	5.88 (0.52)	6.07 (1.23)
		p=0.009, *d*=1.47		**p=0.033; *d*=0.44**				
	95% CI of mean differences between HCV and PAS	**-0.23, -0.04**	-0.09, 0.41	**-0.55, -0.03**	-51.66, 199.60	-6.35, 8.76	-0.47, 0.22	-1.08, 0.80
AR2	HCV	38.54 (0.14) †	36.75 (0.52) †	1.79 (0.47) †	207.07 (120.67) †	151 (12)	6.65 (0.61)	5.59 (1.45)
	PAS	38.64 (0.06)	35.45 (0.77)	2.19 (0.75)	305.40 (143.72)	150 (19)	6.72 (0.91)	5.83 (1.48)
		p=0.045, *d*=0.93	**p=0.017, *d*=0.46**	**p=0.009; *d*=0.64**	**p=0.034, *d*=0.74**			
	95% CI of mean differences between HCV and PAS	**-0.19, -0.00**	**0.07, 0.53**	**-0.67, -0.12**	**-187.53, -9.14**	-10.87, 12.84	-0.68, 0.43	-1.36, 0.88

p value at significant level and the corresponding Cohen's *d* were provided.

* Main effect for condition; † Simple main effect test indicating significant difference between the HCV and PAS conditions in the test bout

Vitae

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