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Title Page

Manuscript title: Reduction of physiological strain under a hot and humid environment by a hybrid cooling vest

Brief running head: Reduction of physiological strain by a hybrid cooling vest

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Abstract
Cooling treatment is regarded as one of good practices to provide safe training conditions to athletic trainers in the hot environment. The present study aimed to investigate whether wearing a commercial lightweight and portable hybrid cooling vest that combines air ventilation fans with frozen gel packs was an effective means to reduce participants' body heat strain. In this within-subject repeated measures study, 10 male volunteers participated in two heat-stress trials (one with the cooling vest – COOL condition, and another without – CON condition, in a randomized order) inside a climatic chamber with a controlled ambient temperature 33 °C and relative humidity (RH) 75% on an experimental day. Each trial included a progressively incremental running test, followed by a 40 min post-exercise recovery. Core temperature (T_c), heart rate (HR), sweat rate, rating of perceived exertion (RPE), exercise duration, running distance, power output, and sweat rate were measured. When comparing the two conditions, a non-statistically significant moderate cooling effect in rate of increase in T_c (0.03±0.02 °C/min for COOL vs. 0.04±0.02 °C/min for CON, p=0.054, d=0.57), HR (3±1 bpm/min for COOL vs. 4±1 bpm/min for CON, p=0.229, d=0.40), and physiological strain index (PSI) (0.20±0.06 unit/min for COOL vs. 0.23±0.06 unit/min for CON, p=0.072, d=0.50) was found in the COOL condition during exercise. A non-statistically significant (p>0.05) trivial cooling effect (d<0.2) was observed between the COOL and CON conditions for measures of exercise duration, running distance, power output, sweat rate and RPE. It is concluded that the use of the hybrid cooling vest achieved a moderate cooling effect in lowering the rate of increase in physiological strain without impeding the performance of progressively incremental exercise in the heat.

Keywords
effect size; physiological strain; training conditions

INTRODUCTION

Training in hot conditions poses a great risk in exertional heat stroke (30) and even in fatal incidents (10). Proper measures should be taken to offer safer training conditions through preventing heat injuries of athletic trainers in hot weather. Cooling treatment is considered as one of good practices regarding exertional heat illness (24). It is suggested that continuous cooling has a significant potential to slow down the increase of heat strain accumulated during exercise and maintain exercise performance (5). However, limited attention has been paid to the usage of cooling modalities during training sessions probably because of their inferior cooling rates (24) and practical issues (34).

The efficacy of cooling treatments during exercise can vary from different cooling modalities and exercise modes (3, 28). Torso cooling has a great potential for heat dissipation regarding a larger surface area than other partial cooling (34). Abundant evidences in the efficacy of cooling garments with either passive or active system in reducing body heat strain have been shown elsewhere (2, 21, 23). Active cooling suits that utilize air or liquid circulation mainly contribute to conductive, convective, or evaporative heat loss (18, 20). Passive cooling garments often include a cooling source such as phase change materials as heat exchange mediums (22) to absorb heat from the wearer when the materials change from a solid to a liquid state (29). Research on the use of hybrid cooling garments that combine two or more passive and/or active cooling systems during exercise-heat stress is relatively sparse. Earlier studies showed that the air-liquid cooling garments appeared to be limited in alleviating physiological and perceptual strain as compared to individual air- or liquid- cooling garments under uncompensable heat stress (9, 13). By incorporating with air fans and phase change material packs, the portable hybrid cooling garments were recently developed by Song and Wong (31) and Song et al. (32). These garments were found to be effective in reducing local skin temperatures and improving thermal comfort when comparing with no cooling conditions. While the aforementioned hybrid cooling garments are developed for military and industrial settings, the scenario is different in aerobic exercise training.

Differing training goals such as the improvement of aerobic capacity are to be considered when structuring the endurance training protocols in respect to exercise intensity and duration (19). Progressively incremental exercise mode can elicit rapidly changing physiological responses (17) and measure exercise capacity of competitive athletes (16). The effects of cooing modalities used during the progressively incremental exercise on physiological responses remain unclear. The present study aims to improve training practice in hot conditions by determining the effectiveness of wearing a portable and lightweight hybrid cooling vest in reducing body heat strain without impeding the performance of progressively incremental exercise.

METHODS

Experimental Approach to the Problem

No laboratory acclimatization sessions were performed for the participants prior to the experiment. The participants were required to complete the experiment on one day. The entire experimental program included pre-exercise rest (30 min rest outside the climatic chamber and then 30 min rest inside), followed by two heat stress trials each consisted of a progressively incremental running and post-exercise recovery, and an additional rest period between the two trials. With a within-subjects repeated measures experimental design, the participants completed two heat-stress trials in a randomized and counterbalanced order: 1) a heat-stress trial in which the participants wore a hybrid cooling vest (COOL), and 2) a heat-stress trial in which no cooling vests were worn by the participants (CON). The measurements designed for the experimental program included the indicators of exercise performance (e.g., exercise duration, distance, and power output), physiological responses (e.g., body core (intestinal) temperature, and heart rate), and perceptual sensation (e.g., rating of perceived exertion). In order to provide 80% of statistical power and to reach an error of probability of less than 5% for detecting 0.8 °C difference in body core temperature with a standard deviation of around 0.45 °C (35), a sample size of 10 was determined as a priori for the experimental program.

Hybrid Cooling Vest

A commercially available hybrid cooling vest (Figure 1) that combines passive and active cooling methods was employed in this study. While its passive cooling method mainly relies on frozen gel packs via conductive heat transfer, its active cooling method that utilizes air ventilation enhances evaporative and convective heat loss. The vest is not labeled for the use under discussion. Three frozen gel packs, each with a covering area of 160 cm^2 and a mass of 150 g, are inserted into the pockets on the belly and the back of the vest. These nontoxic packs consist of 89% water based gel and 11% of fire retardant Textilence fabric. The melting point and latent heat of fusion of the pack is 2.95 °C and 334.94 kJ/kg, respectively. The small detachable electronic fans (with a diameter of 10 cm) powered by four alkaline batteries (1.5V) are mounted to the lower back of the vest and blow on the torso. Each fan blowing on the torso supplies approximately 21 L/s of airflow rate (~11.7 m/s of air velocity measured by the anemograph, Hot Wire Anemometer, Lutron®, Taiwan).

The outer layer fabric (Teflon® fabric protector, DuPont™) of the vest is light (i.e., 75 g/m^2), thin (i.e., 0.12 mm), and airproof. Its water vapor permeability is approximately 940 g/m^2/day. The inner layer of the vest is made of meshed fabric, with a weight of 94 g/m^2 and thickness of 0.3 mm. The total weight of the cooling vest, with batteries, is around 1.0 kg. The cooling power of the vest was previously tested with an average of 74 W lasting for 2 hours based on the manikin test in an environmental chamber (with temperature of 35 °C, 65% RH, and air velocity of 0.3 m/s) (25). The cooling vests that suit the body size of the participants were used.

Subjects

Ten male volunteers participated in the experiment. All the participants did not have cardiovascular disease, esophageal disease or other known health problems and they were considered apparently healthy. They practised sports around three times per week and were considered physically active. The participants were instructed to avoid consumption of alcohol and smoking on the day before and the day of testing. The participants were briefed clearly about the details of the climatic chamber treadmill test, its objectives, requirement for participation, potential risks prior to the experiment, and the right to quit the test at any time. Subsequently, they signed a consent form approved by the Human Subjects Ethics Sub-committee of the authors' institution. Average (with standard deviation) age, weight, height, and estimated body surface area ($A_D = 0.007184 \times \text{Height(cm)}^{0.725} \times \text{Weight(kg)}^{0.425}$) (14) of participants were 22 (5) years (ranges from 18 to 32 years), 65 (6) kg (ranges from 57 to 75 kg), 171 (5) cm (ranges from 165 to 182 cm), and 1.74 (0.08) m^2, respectively.

Procedures

Initially, the participants ingested a calibrated core temperature capsule with warm water prior to sleep on the night before they reported to the laboratory. This schedule ensured that the capsule was in the intestine and with a more stable core temperature (8) to avoid the confounding effect of food and drinks (36). Upon arrival at the laboratory, the participant was fed with a breakfast or snack (1048.5 kcal, 11.2 g carbohydrates, 7 g fat, and 9 g proteins) and 150 ml warm water (37.00 ± 0.09 °C) (11). After a proper briefing on the protocol of treadmill test, the participant was asked to complete the basic demographic information including name and age. Height was measured to the nearest centimeter by a wall-mounted ruler. Afterwards, they rested outside the chamber in an environmental condition of 23 °C and 55% RH for 30 min. This procedure was to stabilize the initial core temperature of the participants. The participant was then asked to wear a standard sportswear (i.e., a t-shirt, a pair of shorts and sports shoes with thermal insulation of 0.3 clo) and to rest on a backless chair inside the chamber for another 30 min. This was the heat acclimation session for acute-adaptation to the heat in the laboratory settings (1). The controlled climatic chamber (LabTester, KSON Ltd., Taiwan) maintained the ambient condition at 33 °C and 75% RH with partial water vapor pressure of 3750 Pa, which simulated a hot and humid environment.

Each participant was randomly assigned to undergo two heat-stress trials (one with cooling vest – COOL condition, and another without – CON condition) in one experimental day and in a counter-balanced order. Each trial included a progressively incremental running test (Figure 2) and a 40 min post-exercise recovery. The cooling vest was only applied during the exercise and 40-min recovery in the trial of COOL condition. The participants ran at a progressively increasing speed and slope on a motorized treadmill (h/p/cosmos® pulsar, Germany). The running test was terminated when the participants' core temperature reached 38.5 °C threshold (3) or when the participants were exhausted and requested to stop. Upon the termination of the running test, the participants made active recovery for 10 min and passive recovery for 30 min, both inside the chamber. An additional resting period was provided between the two trials, in which the participants were asked to recover outside the chamber for 20 min or sooner to bring their core temperature down to the initial value before the first run. Prior to the second heat-stress trial, the participants were requested to change another dry standard sportswear. A registered nurse was engaged to station inside the chamber throughout the whole exercise and to provide medical care in case of emergency.

Measurements and Calculations

Core temperature was measured by an ingestible and disposable capsule (CorTemp, the USA). A day before the test, a calibration procedure was executed to ensure that the capsule functioned properly with an accuracy of ± 0.1 °C (1). Inside a water cup (approximately 85 ml of water), the capsule measured the water temperature from 42 °C to 30 °C (15) at a sampling frequency of 30 s. The temperatures recorded by the capsule were checked against a certified temperature probe with a precision of 0.01 °C (Precision Thermometer, Lutron®, Taiwan). The results of the calibration showed that the differences in temperatures recorded by the thermometer and by the used capsules were 0.04 (± 0.03) °C. The capsule was connected remotely to a data logger that was monitored by a small digital camera inside a bum bag. The bag was attached to the waist of the participant and the core temperature was recorded continuously during the entire experiment.

Heart rate was recorded wirelessly by a heart rate monitor (Polar Wearlink, the USA) at a sampling frequency of 60 s during the 30-min rest outside the chamber and it was continuously collected by another belt (Polar T34 Transmitter, the USA) at a sampling frequency of every second during any activities inside the chamber. The heart rate transmitter transferred the data to the computer via a sensor on the treadmill that recorded the running distance and exercise duration synchronously. Power output was calculated by the treadmill speed and slope and body weight.

Body weights (with underwear) of the participants were measured inside the climatic chamber before and after each running period by an electronic scale with a precision of ±0.01 kg (E-SNO-PSL-150KPC, Sam Hing Scales Fty. Ltd., Hong Kong). To standardize the hydration status of the participants of the two trials, the weight of warm water intake in five minutes prior to the second trial was controlled by the differences of the body weight before and after exercise. The volume of water intake was recorded. Sweat rate (SR, in L/h unit) was calculated by the body weight change as a function of exercise time after correcting for any urine loss and total water intake (assuming water volume of 1 L = 1 kg). No participants passed any urine during the entire test or had water intake during exercise. In addition, the participants were asked to report their overall perception on the entire exercise by using ratings of perceived exertion (RPE) (from 0=rest to 10=extremely hard effort) (7).

The physiological strain index (PSI) describes heat strain in quantitative terms based on heart rate and core temperature records in humans (26). The output is scaled from 0 to 10, where 0 represents no strain and 10 very high physiological strain. The mathematical expression of PSI is shown in Eq. (1) (33).

$$\mathbf{PSI} = \frac{5 \times (T_{ci} - T_{c0})}{39.5 - T_{c0}} + \frac{5 \times (HR_i - HR_0)}{HR_{max} - HR_0} \qquad (1)$$

where T_{c0} and HR_0 is the minimum core temperature and heart rate during the 30 min rest outside the chamber, respectively; T_{ci} and HR_i are the simultaneous core temperature and heart rate, respectively, taken at any time while the participant is exercising during the whole heat stress trial inside the chamber. HR_{max} is the maximum heart rate of the participant achieved, which is substituted into the equation if it exceeds 180 bpm.

Statistical Analysis

Data of core temperature and heart rate were reduced to average values per minute. Paired t-test was used to assess the statistically significant difference between COOL and CON in measures of exercise time, mean power output, running distance, sweat rate, RPE, rates of change in T_c ($R_{\Delta Tc}$), HR ($R_{\Delta HR}$), and PSI ($R_{\Delta PSI}$). Analysis of the means of change in core temperature (ΔT_c), heart rate (ΔHR), and physiological strain index (ΔPSI) were conducted using a two-way [condition (COOL versus CON) × time point (3rd, 12th, and the last minute during exercise; and 10th, 20th, 30th, and 40th min during recovery)] repeated measures analysis of variance (ANOVA). The Greenhouse–Geisser correction was designated as statistical significance when the Mauchly's Test of Sphericity was violated. The significance level was set at $p<0.05$. Effect size analysis of these measures was also used to indicate small, moderate, or large practical effect noted in the data. A Cohen's *d* of <0.2 is classified as a trivial effect, 0.2–0.4 as a small effect, 0.4–0.7 as a moderate effect and >0.8 as a large effect (12). The results were reported as mean ± standard deviation (SD) and 95% confidence interval (CI) of mean difference between conditions.

RESULTS

Table 1 shows the absolute values of T_c and HR at the end of exercise, and the maximal heart rate of each participant. Neither main effect of condition nor interaction effect between condition and time for ΔT_c, ΔHR, and ΔPSI were observed during exercise (Table 2). During exercise a non-statistically significant moderate cooling effect in $R_{\Delta Tc}$ in the COOL condition (0.03±0.02 °C/min for COOL vs. 0.04±0.02 °C/min for CON; p=0.054, d=0.57, 95% CI: -0.17 – 0.00 °C/min; Figure 3a) was observed, as well as in $R_{\Delta HR}$ (3±1 bpm/min for COOL vs. 4±1 bpm/min for CON; p=0.229, d=0.40, 95% CI: -0.95 – 0.26 bpm/min; Figure 3b) and in $R_{\Delta PSI}$ (0.20±0.06 unit/min for COOL vs. 0.23±0.06 unit/min for CON; p=0.072, d=0.50, 95% CI: -0.06 – 0.00 unit/min ; Figure 3c).

Non-statistically significant differences and trivial effects were found in exercise time (23.11±6.51 min for COOL vs. 22.09±6.57 min for CON; p=0.456, d=0.16, 95% CI: -1.94 – 3.99 min), running distance (2780±919 m for COOL vs. 2649±925 m for CON; p=0.517, d=0.14, 95% CI: -310 – 572 m), average power output (115±24 W for COOL vs. 111± 23 W for CON; p=0.261, d=0.17, 95% CI: -3 – 10 W), SR (1.41±0.60 L/h, for COOL vs. 1.43±0.85 L/h for CON; p=0.937, d=0.03, 95% CI: -0.60 – 0.56 L/h), and RPE (5.00±2.05 unit for COOL vs. 5.20±1.99 unit for CON; p=0.591, d=0.10, 95% CI: -1.01 – 0.61 unit) between the two conditions.

The results of ANOVA revealed that neither main effect of condition nor interaction effect between condition and time for ΔT_c, and ΔHR were detected during recovery (Table 2). A main effect of condition was found for ΔPSI, indicating that the decline in the physiological strain index was significantly accelerated in the COOL condition (3.15±1.52 unit/min for COOL vs. 2.86±1.50 unit/min for CON; p=0.037, d=0.19, 95% CI: 0.03 – 0.56 unit/min). However, a non-statistically significant trivial cooling effect in $R_{\Delta Tc}$ (0.015±0.007°C/min for COOL vs. 0.013±0.007°C/min for CON; p=0.565, d=0.15, 95% CI: -0.003 – 0.005 °C/min; Figure 3d) was found in the COOL condition, as well as in $R_{\Delta HR}$ (2±0 bpm/min for COOL vs. 2±0 bpm/min for CON; p=0.958, d=0.00, 95% CI: -0.18 – 0.19 bpm/min; Figure 3e) and in $R_{\Delta PSI}$ (0.10±0.018 unit/min for COOL vs. 0.10±0.027 unit/min for CON; p=0.479, d=0.16, 95% CI: -0.01 – 0.01 unit/min; Figure 3f) during the recovery period.

DISCUSSION

Although physiological responses showed non-statistically significant differences between the COOL and CON conditions, the hybrid cooling vest had a moderate cooling effect on reducing the rate of increase in physiological strain. In terms of the magnitude of rate of increase in core temperature, similar cooling rates have been observed elsewhere. Webborn et al. (35) found that the rate of core temperature increase was significant lower with wearing an ice vest (0.028±0.04 °C/min) than that with no cooling (0.041±0.004 °C/min) during intermittent sprint exercise. Both of Webborn et al. (35)'s and the current studies employed high-intensity exercise protocols that could yield substantial heat gain in hot conditions. When comparing with the non-cooling condition, cooling during exercise contributed to reducing the gain in core temperature under exercise-heat stress. PSI represents the overall state of physiological strain accounting for thermo-physiological and cardiovascular strain; however, the rate of the increase in this indicator was not well documented and thus was not comparable with previous studies. Overall, the beneficial effect to slow down the increase in physiological strain supports the use of the hybrid cooling vest during incremental running exercise in hot and humid environment. A statistically significant difference in ΔPSI between these conditions was observed during post-exercise recovery. By contrast, Hadid et al. (18) found that the use of an air-cooled vest could significantly reduce thermo-physiological strain during exercise rather than during recovery period, probably because the marked pumping effect was absent. A non-statistically significant trivial cooling effect in sweat rate between the COOL and CON conditions was observed and may be due to the following. The highly humid environment may reduce the vapor gradient between the human body and the environment that hinders moisture evaporation. Sweat evaporation might also be inhibited because of the insulation of the vest.

Wearing the hybrid cooling vest indeed maintained exercise performance with reducing the gain in physiological strain, which can also be regarded as a considerable potential in practice for cooling during exercise (5). Significant improvements in exercise performance (>10%) with wearing the cooling vests, coupled with a significant reduction of over 20% in the rates of increase in T_c and/or HR, compared with those without cooling vests, have been reported elsewhere (2, 21). These studies adopted the exercise protocols specific to relatively long exercise duration (i.e., over 120 min) and moderate exercise intensity. Such protocols may allow adequate thermal strain experienced and sufficient volume of the cooling applied (27, 34), and thus the improvement in exercise performance, if any, can be observed. The results of the alterations of exercise performance found here may not be comparable with other studies, as exercise protocols have varied widely. In the current study, the high-intensity nature of the progressively incremental exercise protocols may speed up the physiological threshold or exhaustion of the athletes under a safe and control environment (4). Table 1 shows that the heart rate of the participants nearly reached over 90% of age-predicted maximal heart rate at the end of exercise, while most of the participants stopped exercise because their core temperatures reached the prescribed threshold. Correspondingly, RPE did not vary to a large extent between the COOL and CON conditions given that the responses of exercise-heat stress on perceived exertion are largely dependent upon the intensity of exercise (6). Even though it is unclear that their exercise performance was limited by thermoregulatory, cardiovascular systems or musle fatigue, the exercise was terminated within a short period at prescribed exhaustion thresholds, regardless of the COOL or CON conditions. There has been a sizable amount of research investigating the effects of cooling vests on exercise performance in a thermal environment. Systematic reviews conducted by Tyler et al. (34) and Bongers et al. (5) revealed that cooling during exercise could significantly improve exercise performance even though changes in physiological or perceptual responses were absent. Although they highlighted that its effects largely relied on the level of thermal strain experienced (i.e., compensable vs. uncompensable heat stress) and type of cooling modalities (i.e., ice vest vs. other cooling packs), the underlying correlation between type of exercise and cooling during exercise was yet to be determined. Therefore, methodologies differences in terms of different cooling strategies and exercise protocols imply that further research is required to clarify the impacts of exercise mode on the effectiveness of the cooling modalities used during exercise.

Limitations of the current study are recognized. The two testing trials (i.e., COOL and CON) were completed subsequently in an experimental day. Although efforts had been made to standardize the hydration level of each participant prior to the two exercise bouts, the confounding effect of trial order on thermoregulation status of participants remains unknown. Individual factors including physical fitness level and body fat that are associated with human vulnerability to exercise-heat stress were not fully scrutinized. Further examination of skin temperatures would assist in interpreting the cooling effect of the hybrid cooling vest on physiological responses.

PRACTICAL APPLICATIONS

This study attempts to improve training practice by offering proper cooling modality during training sessions in hot conditions. Unlike most of bulky and heavy personal cooling suits, the current hybrid cooling vest with light weight would not impose excessive burden while using it during exercise. The findings of the current study indicated that the use of a portable and lightweight hybrid cooling vest has a potential in practice to cool athletes with a moderate cooling effect to slow down the increase in core temperature, heart rate, and physiological strain index and maintain their exercise performance in a hot and humid environment.

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Note: Numerical mark was represented as individual data point. For each condition mean value and 95% confidence interval (error bar) were presented.

Table list

Table 1 Core temperature (T_c) and heart rate (HR) at the end of exercise, and the age-predicted maximal heart rate of the participant

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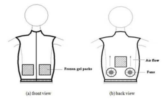
Table 1 Core temperature (T_c) and heart rate (HR) at the end of exercise, and the age-predicted maximal heart rate of the participant

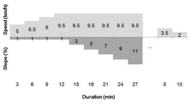
Participant/Parameter	**COOL**		**CON**		**Age-predicted maximal HR**[a]
	T_c	HR	T_c	HR	
1	38.5	183	38.5	189	202
2	38.5	195	38.5	196	200
3	38.5	184	38.5	183	202
4	38.23	202	38.04	193	188
5	37.79	197	38.51	199	201
6	38.5	172	38.5	180	200
7	38.5	181	38.52	178	201
8	38.5	183	38.5	187	197
9	38.5	198	38.5	201	194
10	38.5	195	38.5	186	190
Frequency of termination due to the prescribed threshold	Temperature threshold (8) Volitional exhaustion (2)		Temperature threshold (9) Volitional exhaustion (1)		

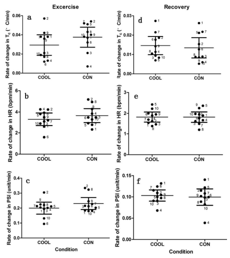
[a]: Age-predicted maximal heart rate = 220 – Age.

Table 2 Results of a two-way (condition × time) analysis of variance with repeated measures

Parameter	Condition	Mean (SD)	95% confidence interval of mean difference	Main effect of condition	Interaction effect
Exercise					
ΔT_c (°C)	COOL	0.30 (0.15)	-0.16 – 0.03	F=2.586,	F=2.173,
	CON	0.37 (0.17)		p=0.142	p=0.173
ΔHR	COOL	42 (9)	-11 – 6	F=0.582,	F=0.113,
(bpm)	CON	45 (11)		p=0.465	p=0.768
ΔPSI	COOL	2.36 (0.63)	-0.66 – 0.21	F=1.362,	F=0.605,
(unit)	CON	2.59 (0.71)		p=0.273	p=0.484
Recovery					
ΔT_c (°C)	COOL	0.14 (0.50)	-0.11 – 0.20	F=0.453,	F=0.013,
	CON	0.10 (0.41)		p=0.526	p=0.998
ΔHR	COOL	60 (7)	-4 – 8	F=0.840,	F=2.422,
(bpm)	CON	58 (12)		p=0.395	p=0.099
ΔPSI	COOL	3.15 (1.09)	0.03 – 0.56	F=7.924,	F=0.662,
(unit)	CON	2.86 (1.05)		p=0.037	p=0.588


Frozen gel packs
Air flow
Fans
(a) front view
(b) back view


Speed (km/h)
Slope (%)
5
6.5
8
9.5
9.5
9.5
9.5
9.5
9.5
3.5
2
1
1
1
1
3
5
7
9
11
3
6
9
12
15
18
21
24
27
5
10
Duration (min)


Excercise
Recovery
a
b
c
d
e
f
Rate of change in T_c (°C/min)
Rate of change in HR (bpm/min)
Rate of change in PSI (unit/min)
COOL
CON
Condition