INFLUENCES OF RAISED AMBIENT TEMPERATURE ON CARDIORESPIRATORY PERFORMANCE IN A 3-MINUTE STEP TEST

HIDEYUKI TANAKA1*, 2, MASAHIRO SHIMODA3 AND TOSIMICHI ISHIMIYA4, 5

1 Laboratory of Motor Behaviour, Advanced Health Science, Institute of Bio-Applications and System Engineering, Tokyo University of Agriculture and Technology, 2-24-16 Nakacho, Koganei, Tokyo 184-8588, Japan
*Email: tanahide@cc.tuat.ac.jp
2 Biotechnology and Life Science, Tokyo University of Agriculture and Technology
3 Health and Amenity Science, Tokyo University of Agriculture and Technology
4 Waseda Sports Sciences Research Centre, Waseda University
5 Global Leader Career Network, University of Tsukuba

ABSTRACT
We investigated the effects of raised ambient temperature on cardiorespiratory performance in a 3-min step test. Subjects repeatedly performed the step exercise under three ambient thermal conditions. A cardiorespiratory fitness index was computed from heart rate (HR) measurements during a recovery period after the exercise. Raised ambient temperature was associated with significantly increased HR not only during the rest period before exercise but also during the recovery period. The cardiorespiratory fitness index for the high temperature condition was significantly poorer than those for the moderate conditions. The variability of the pre-exercise HR among the three thermal conditions was highly correlated with the variability of the cardiorespiratory index. These results indicate that the 3-min step test should be performed under identical ambient thermal conditions and, if necessary, cardiorespiratory fitness evaluation based on HR recovery after the 3-min step exercise should be corrected for individual acclimation states or heat stress properties.

Keyword: cardiorespiratory capacity; heart rate; heat stress; acclimation; young adult

INTRODUCTION
Correct assessment of physical fitness is essential in protecting workers against the occupational health risks. Particularly in physically demanding jobs, cardiorespiratory fitness or aerobic capacity is more important for overall health. It is also a major determinant of the ability to perform work tasks and of a physical tolerance of prolonged workload imposed on workers. Although maximal oxygen uptake (VO2 max) is the best indicator of aerobic capacity, its measurement requires highly-specific and costly equipment and requires that participants exercise continuously until total exhaustion. Because of these drawbacks, more convenient tests and measurements of aerobic capacity have been developed and utilized in research to replace the direct measurement of VO2 max. The step test is one alternative evaluation of cardiorespiratory fitness based on heart rate (HR) measurements during sub-maximal exercise of relatively moderate intensity.

There are many versions of step tests, among which the earliest and most popular is the Harvard Step Test developed by Brouha (1943). Step tests in general require simple, low-cost equipment such as a step bench, a stopwatch and a metronome. In step tests, participants step up onto and down off of a bench for a particular interval at a constant rate. The HR measured during a recovery period after the stepping exercise (recovery-HR) is completed for the computation of a cardiorespiratory fitness index (CFI). The principle of the step test is based on empirical observations that HR proportionally increases with the load intensity.
of exercise and correlates linearly with oxygen uptake (VO$_2$) (Sunagawa et al., 1984). Therefore, it is assumed that as an individual’s cardiorespiratory capacity rises, his or her recovery-HR will more rapidly return to the pre-exercise resting state. A large body of previous work has shown that fitness indices based on recovery-HR measurements in step tests are valid for the assessment of cardiorespiratory fitness (Mc Ardle et al., 1972; Watkins, 1984; Francis and Brasher, 1992; Santo and Golding, 2003).

While step tests keep costs minimal, the test results tend to vary with equipment, procedures and/or conditions. For example, the dimensions of the step bench can influence test performances (Liu and Lin, 2007; Yuan et al., 2008). To enhance the validity of step tests, adjustments of the bench height to participants’ body height or leg length should be considered so that the biomechanical efficiency of stepping movements is identical between different-sized participants. However, the influence of the step bench dimensions on test performances should not present a significant disadvantage if the same step tests are repeatedly used within individuals or a local population (e.g., school, company, and nursing home) as they are sometimes used to confirm the effectiveness of an exercise program in promoting cardiorespiratory fitness. Using step tests in these ways, ambient climatic conditions in the testing milieu may be yet another factor that influences test performances.

Prolonged exercise in a hot and humid environment poses severe challenges to the thermoregulatory mechanisms of the human body. Under passive heat stress conditions (i.e., exposure to elevated ambient temperature), human skin blood flow can increase from a baseline of approximately 300 up to 7500 ml/min and is accompanied by an increase in cardiac output of 13 l/min (Rowell et al., 1969; Rowell, 1986). Raised cardiac output is primarily mediated by increased HR because the stroke volume does not change or only slightly increases under such thermal stresses (Damato et al., 1968; Rowell et al., 1969; and for review, also see Crandall and Gonzalez-Alonso, 2010). Indeed, high ambient temperature has been shown to increase HR during both the exercise period and the post-exercise recovery period, even during light-to-moderate-intensity exercise (i.e., 35 to 45%VO$_{2\text{max}}$) (Torii et al., 1986). Considering these findings, we can predict that if step tests are performed under heat-stressful conditions such as those during the summer, then cardiorespiratory fitness will be assessed as being lower than it would be under comfortable conditions during other seasons.

The present study was designed to test whether the cardiorespiratory fitness performance in a 3-min step test was affected by raised ambient temperature. We hypothesised that the recovery-HR after the step test would considerably increase during hot environmental conditions. In the assessment system of the 3-min step test, a CFI is calculated from recovery-HR according to the following formula: the time of exercise (s) / the sum of three recovery-HR measurements (beats per min) x 100. In the theory, when recovery-HR increases, the value of the CFI decreases, indicating a relative deterioration of the cardiorespiratory capacity. However, whether increased recovery-HR due to heat stress alone represents an actual reduction of cardiorespiratory fitness remains unclear. To clarify this point, young adult participants were required to repeatedly perform 3-min step tests under different thermal conditions. Results showed that raised ambient temperature significantly increased HR during recovery periods after the step exercise and thus reduced the cardiorespiratory fitness index. We discuss the need to correct for such a possible apparent (or temporal) reduction of cardiorespiratory performance due to elevated ambient temperature.

METHODS

Subjects

Twelve healthy male university students aged 21-25 years participated in this study with written informed consent. This was a convenience sample from a classroom setting. Prior to any testing, participants were screened for cardiovascular, pulmonary and orthopaedic problems through a questionnaire to assess their readiness for physical activity and health history. None of the participants were taking any medications and none were smokers. None of the participants had been taking intentional regular exercise for the prior two years. This study was approved by the local ethics committee at the first author’s institution. All experimental procedures were carried out in accordance with the Declaration of Helsinki.
Means and standard deviations of the subjects’ body heights and weights were 173.4±7.8 cm and 64.0±8.1 kg, respectively, at the first participation in a series of experiments in May. The group’s mean body weight slightly decreased to 62.6±7.2 kg at the last participation in July.

**Experimental procedures**

Participants were instructed to refrain from exercising or consuming alcohol for 24 hours prior to the step tests and from consuming caffeine on the day of an experiment or eating within 2 hours before the start of the test. They were free to drink mineral water until 1 hour prior to the tests. To minimize any possible effects of differences in clothing material characteristics such as air permeability and moisture evaporation on physiological parameters during exercise (Ciesielska et al., 2009), all subjects performed the 3-min step tests wearing a black T-shirt made of 100% cotton and a black half-pant made of 100% polyester throughout the experiments.

In the step test, subjects were asked to step up onto and down off of a step bench of 40 cm in height for 3 min with a cadence of 30 steps per min. An electronic metronome (Digi-timer TOP60, Molten, Japan) provided a sound cue to control subjects’ stepping cadences. These testing parameters were determined according to a protocol of the physical fitness test battery (the former version) for Japanese populations that was standardized by the Sports and Youth Bureau of the Ministry of Education, Culture, Sports, Science and Technology in Japan. In this study, the test period consisted of a pre-exercise rest for 5 min, a preparatory interval for 1 min, step exercise for 3 min and a post-exercise recovery period for 4 min. Subjects immediately sat down on the bench upon completion of the step exercise and maintained natural breathing during the recovery period. One subject was unable to accurately maintain the step cadence because of exhaustion, although he did not retire from the 3 min step exercise. Therefore, his data were excluded from analysis.

The experiment was performed under three thermal conditions: natural moderate (Mod), natural heat (Heat) and artificial moderate (A-Mod). The Mod and Heat experiments were repeated in a gymnasium in May and July, respectively. The A-Mod experiment was performed in an air-conditioned room one week before the Heat experiment. The ambient temperature and relative humidity for the A-Mod experiment were maintained at levels similar to those measured in the Mod experiment. All three experiments lasted for any one hour between 10 a.m. and 12 a.m. In the A-Mod experiment, the subjects entered the air-conditioned room and then remained seated on a bench for 30 min prior to the start of the test session. Climatic data from the experiments are summarised in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Mod</th>
<th>A-Mod</th>
<th>Heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Temp. (°C)</td>
<td>18.5±0.3</td>
<td>20.2±0.4</td>
<td>29.7±1.8</td>
</tr>
<tr>
<td>Humidity (%)</td>
<td>62.9±2.8</td>
<td>54.8±4.0</td>
<td>60.8±5.4</td>
</tr>
<tr>
<td>WBGGT (°C)</td>
<td>16.2±0.3</td>
<td>17.2±0.6</td>
<td>26.5±1.3</td>
</tr>
</tbody>
</table>

Climatic data were collected at every 30 min during the experiments. Means and standard deviations are presented. WBGGT, wet bulb globe temperature.

**Measurements**

HR was recorded each second in a unit of beats per min (bpm) with a HR monitor (S810i, POLAR, Finland) throughout the test period. In addition to this, the baseline resting HR was measured with subjects in a supine position as self-recorded by subjects immediately after awaking in the morning. Resting HR measurement was repeated five days before or after each experiment day, but within one week. After the exclusion of minimal and maximal values, the remaining three measurements were averaged to represent the resting HR for each experiment.

Sympathetic nervous system activation under the three ambient temperature conditions was determined by using a hand-held analyser to automatically monitor salivary amylase activity (CM-2.1, NIPRO, Japan). A higher salivary amylase activity indicates a more heightened state of arousal (Yamaguchi et al.,
Saliva was collected for 30 sec during the pre-exercise rest period on a disposable cartridge specific for the analyser. A questionnaire was used to estimate the environmental stress level for each subject. Subjective assessments of the ambient conditions based on subjects’ own feelings were scored using a visual analogue scale (VAS). The subjects were asked to determine the point on the scale that they thought most appropriate to express their feelings regarding five aspects of environmental stress as follows: 1) very cold to very hot (i.e., “hotness”), 2) comfortable to uncomfortable (i.e., “discomfort”), 3) no sweating to heavy sweating (i.e., “sweating”), 4) very dry to very humid (i.e., “humidity”) and 5) completely acceptable to completely unacceptable (i.e., “unacceptability”). The determined point on the scale was transformed into a rating score on the environmental stress from 0 to 10 points. These judgments were made at the beginning of each pre-exercise rest period. In order to quantify the intensity of the 3-min step exercise, a rating of perceived exhaustion (RPE) was also scored with a VAS ranging from much rested to extremely exhaust. The VAS score of RPE was transformed into a rating from 6 to 20 points corresponding to the Borg scale (Borg, 1982). RPE judgment was performed at the end of the post-exercise recovery period.

Data analysis

Successive HR data recorded throughout the test period were smoothed with a simple moving average of 5 successive data points. Next, HR measurements from the pre-exercise rest period (HRpre) and the exercise period (HRexe) were calculated by averaging the smoothed data over the last 60 sec and the last 10 sec of each respective period. Data from every 30 sec from 1-, 2- and 3-min of the post-exercise recovery period were averaged to produce three recovery-HR measurements, i.e., HRrec1, HRrec2 and HRrec3, respectively. These recovery-HR measurements were used to calculate a CFI according to the following formula: Step test index = 180 / (HRrec1+HRrec2+HRrec3) x 100.

HR measurements were analyzed using a repeated-measures two-way ANOVA for the three ambient thermal conditions (Mod, A-Mod and Heat) vs. the five test periods (HRpre, HRexe, HRrec1, HRrec2 and HRrec3). The remaining data were analyzed with repeated-measures one-way ANOVAs for the ambient thermal condition factor. The Greenhouse-Geisser correction was employed when sphericity was violated. Tukey’s HSD post-hoc testing was conducted for a multiple comparison, if significant main effects of the ambient thermal condition existed.

RESULTS

HR measurements varied with raised the ambient temperature during a 3-min step test. A two-way ANOVA revealed significant main effects of the ambient thermal condition ($F(1.2, 12.4)=6.0, p<0.05$) and test period ($F(2.1, 21.2)=332.8, p<0.01$). There was a significant interaction between these two factors ($F(8, 80)=2.1, p<0.05$). Next, repeated-measures one-way ANOVAs were carried out separately for the five test periods. Figure 1 shows mean changes of HR as a function of the test period. A significant main effect was found for HR in the pre-exercise rest period, HRpre ($F(2, 20)=8.0, p<0.01$). Tukey’s HSD post-hoc tests demonstrated that the mean HRpre value in the Heat condition was significantly larger than that in the A-Mod condition ($p<0.01$). The mean value of Heat was also larger than that of Mod, but this difference was statistically marginal ($p=0.075$). There was no difference between A-Mod and MOD ($p=0.244$). For HR during the post-exercise recovery period, significant main effects of the ambient thermal condition were found for HRrec2 ($F(2, 20)=4.4, p<0.05$) and HRrec3 ($F(2, 20)=7.0, p<0.01$), but not for HRrec1 ($F(1.2, 12.2)=3.5, p=0.079$). Interestingly, there was no significant effect of the ambient condition on HR at the end of the step exercise period, HRexe ($F(2, 20)=2.4, p=0.117$).

To further determine the effect of high ambient temperature on HR in the post-exercise recovery period, the step test index was calculated and analysed using a repeated-measures one-way ANOVA. Figure 2 shows comparisons of the group means of the step test index between the three ambient thermal conditions. There was a significant main effect of the ambient conditions ($F(1.2, 11.8)=4.5, p<0.05$). Post-hoc
tests revealed that the mean for the Heat condition was significantly lower than that for the Mod condition ($p<0.05$). Although the difference was not statistically significant, the mean for Heat was also lower than that for A-Mod ($p=0.063$). There was no significant difference between Mod and A-Mod conditions ($p=0.934$). These results indicate that high ambient temperatures reduced the cardiorespiratory fitness performance in the 3-min step test.

In contrast, there were no considerable differences in the resting HR between the three experiment days. Means and standard deviations of the resting HR were 59.0±5.5, 58.9±4.7 and 58.6±4.4 bpm for the Mod, A-Mod and Heat conditions, respectively. A repeated-measures one-way ANOVA revealed that the resting HR was not influenced by the time of the different sessions in which subjects participated in experiments ($F(1.3, 12.6)=0.1, p=0.792$). This result indicates that the HR responses in the abovementioned step test are attributable to exposure to natural (or artificial) environments in the testing room.

To uncover psychological and physiological factors that may cause changes of HR under different thermal conditions, we investigated the responses of salivary amylase activity to raised ambient temperature and participants’ perceptions of environmental stress levels. Means and standard deviations of the salivary amylase activity were 19.6±9.2, 23.6±13.8 and 25.5±26.1 kIU/l for Mod, A-Mod and Heat conditions, respectively. There was no significant main effect of the ambient thermal condition ($F(2, 20)=0.6, p=0.583$), indicating that specific responses of the sympathetic nervous system to high ambient temperature did not occur.

However, there were important differences in the subjective assessments of environmental stress levels between the three thermal conditions. ANOVAs demonstrated significant main effects of the ambient
thermal condition for all of the five measurements of the subjective assessment: hotness ($F(2, 20)=217.0$), discomfort ($F(2, 20)=20.3$), sweating ($F(1.0, 10.4)=37.5$), humidity ($F(2, 20)=20.2$) and unacceptability ($F(2, 20)=10.8$) ($p<0.01$). Statistical results from the post-hoc tests are summarised in Figure 3. There were no significant differences between the Mod and A-Mod conditions except for the perceived hotness; participants felt cooler in the A-Mod condition than in the Mod condition, even though their thermal conditions were very similar (Table 1). For the Heat condition, study participants evidently felt hotter, more uncomfortable, sweeter, and more humid and that the environment was more unacceptable as compared to the Mod and A-Mod conditions. Notably, for the Heat condition, the mean value of “unacceptability” was still smaller than the third point on the VAS, which corresponds to the perception of “somewhat hard, but still acceptable”.

Raised ambient temperature also affected the RPE score (Figure 4). There was a significant main effect of the ambient condition ($F(2, 20)=5.0, p<0.05$). Post-hoc tests demonstrated a significant difference of the mean values between the Heat and A-Mod conditions ($p<0.05$) and a marginal difference between Heat and Mod ($p=0.079$). No significant difference was found between Mod and A-Mod ($p=0.740$). To further investigate the difference in intensity of the 3-min step exercise among the ambient thermal conditions, a method based on HR-reserved (Karvonen et al., 1957) was applied to the present data. Additionally, %HR-reserved as an index of exercise intensity was calculated as follows: $(\text{HR}_{\text{exe}} \text{ – the resting HR}) \div (\text{HR}_{\text{maximum}} \text{ – the resting HR}) \times 100$, where an estimate of the HR maximum is given by $220 \text{ – age}$. Means and standard deviations of the %HR-reserved were $72.3\pm5.9$, $70.8\pm5.1$ and $74.5\pm5.6$ % for Mod, A-Mod and Heat conditions, respectively. Although there was no significant main effect of the ambient thermal condition on measurements of %HR-reserved ($F(1.3, 13.3)=2.3, p=0.145$), the mean for Heat increased as compared to those for the Mod and A-Mod conditions. These results indicate that the study participants could perceive the intensity of the step exercise in the Heat condition as greater than those under the other conditions.
Finally, an additional analysis was performed to investigate the relationship between the HR measurements. Figure 5 shows a log-log plot between the variability of HR for the pre-exercise rest period and that for the step test index. Variability was represented with coefficients of variation (CV). A regression analysis revealed a significant correlation between the two variables ($r=0.847$, $p<0.01$) and linearly proportional changes. These data indicate that those subjects who experienced greater changes of HR under different ambient thermal conditions before the exercise showed greater changes of the recovery-HR and vice versa.

**DISCUSSION**

In these experiments, high ambient temperature increased HR during the rest period before the 3-min step exercise but also during the recovery period after exercise. Such an effect of raised ambient temperature was more pronounced at later periods of the recovery than immediately after the end of exercise. The fact that the salivary amylase activity was very stable among the experimental conditions indicates that specific responses of the sympathetic nervous system to high ambient temperature did not occur; thus, the observed HR changes resulted from the differences in ambient thermal conditions alone. These findings strongly support the notion that raised ambient temperature could lead to a temporal (or perceived) underestimation of cardiorespiratory fitness as evaluated using measurements of recovery-HR such as the step test index.

Under severe heat load conditions such as >28 °C of wet bulb globe temperature (WBGT) (i.e., uncompensable heat stress), the temperature gradient between the body core and the skin narrows, and for thermoregulatory purposes, skin blood flow must increase (Kenney and Johnson, 1992; Wendt et al., 2007). Redistribution of cardiac output may deliver some additional blood flow to the skin (Rowell et al., 1965), but an increased HR becomes necessary to ensure adequate cardiac output. This thermoregulatory system would effectively function to increase HR during the pre-exercise rest period and the post-exercise recovery period under the Heat condition.

Contrarily, there appeared to be a lack of effect of elevated ambient temperature on HR variance during the step exercise. This finding is inconsistent with those of previous findings. Torii et al. (1986) showed that high ambient temperature increases HR during exercise of fairly light intensity (e.g., 35 to 45%VO$_{2\max}$). Our subjects reported a range of 12 to 13 points of RPE on the Borg scale under the Heat condition (see Fig. 4). This value corresponds approximately to 60%VO$_{2\max}$, in general (Borg, 1982). Moreover, the %HR-reserved during the step exercise was greater than 70%, on average, as mentioned above. We can predict based on these data that for the subjects in this study, the physical work load of the 3-min step exercise was greater than 60%VO$_{2\max}$. While blood flow in exercising muscle tissues increases with an increase in exercise intensity, skin blood flow must also increase with higher body temperatures for thermoregulatory purposes. Exercise at a higher intensity under high-heat conditions necessitates larger volumes of blood flow in muscle tissues than in skin tissues. If this was the case, raised ambient temperature would become a relatively small effecter of HR changes as the exercise intensity increases. In this view,
the fact that the exercise intensity of the step tests in this study is higher than in previous studies may account for the lack of the effect of raising temperature on HR during the step exercise.

Another alternative explanation for the inconspicuously high HR during the step exercise in the Heat condition concerns a relatively small magnitude of heat stress. The subjective assessments indicated that the Heat condition remained reasonably acceptable for the subjects. Indeed, the mean WBTG during the Heat experiments was lower than 28 °C (see Table 1). If the step tests were performed under more severe heat load conditions, the HR during the step exercise might increase more significantly with greater increases of blood flow to the skin for sweating.

One may suggest that an acclimation to heat stress might not occur from the first experiment (Mod condition) to the last one (Heat condition), resulting in significant increases of pre-exercise HR and recovery-HR, even with the relatively small increase in ambient temperature. It is well known that regular endurance training under high temperature conditions can improve acclimation to heat stress (Franklin et al., 1998; Geor and McCutcheon, 1998). To minimized such an effect, healthy adults who had been undergoing no intentional regular exercise for the previous two years were selected as study participants. Interestingly, there were individual differences in the HR response to changes of the ambient thermal conditions. Particular subjects showed larger variability of HR in both the pre-exercise and recovery periods (see Fig. 5). Possibly, this phenomenon might reflect individual baseline differences in acclimation states or responsivity to heat stress. This issue should be addressed in greater detail in future studies.

Finally, but most importantly, the step test is a convenient test and serves as a measurement of aerobic capacity in field surveys. It can be utilized in workplace settings and provide information available for management of occupational health and safety for workers engaged in jobs in forestry, agriculture, construction and so on (e.g., Yoopat et al., 2002). The present study evidenced that raised ambient temperature and severe heat exposure in the summer could substantially reduce the cardiorespiratory fitness score in the 3-min step test. To enhance the validity of the 3-min step test, the test should be repeated under identical ambient thermal conditions. In other words, researchers performing field surveys must notice that ambient climatic conditions in the testing milieu influence test performances of the cardiorespiratory fitness: a temporal increase in HR due to elevated ambient temperature (>28 °C of WBTG) could lead to the underestimation of the cardiorespiratory fitness.

CONCLUSIONS

Ambient thermal conditions significantly influenced the cardiorespiratory performance in the 3-min step test. A temporal increase in the recovery HR of the step test due to elevated ambient temperature could lead to the underestimation of the cardiorespiratory fitness. To enhance the validity of the 3-min step test, the test should be repeated under identical ambient thermal conditions. If necessary, the cardiorespiratory fitness assessment based on the test performance should be corrected by considering individual acclimation states or responsivity to heat stress.

REFERENCES


H. TANAKA et al.


