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EVALUATION OF WBGT GUIDELINES TO ASSESS THERMAL STRAIN DURING ENDURANCE RUNNING OF JAPANESE HIGH SCHOOL STUDENTS

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ABSTRACT

Background: Endurance running (ER) is a common physical test used in physical education (PE) classes in Japan. To perform ER tests safely, the Wet Bulb Globe Temperature (WBGT) index is monitored. Yet, incidences of heat-related illness are still reported every year. In this study, the thermal strain levels of the Japanese high school students during ER tests were evaluated in both environmental and physiological aspects. **Methods:** A total of 61 male students (Height: 169.7±4.8 cm, Weight: 60.9±10.7 kg) wearing T-shirts and shorts participated in an outdoor ER test during their PE classes (WBGT: 23.1±2.9°C). Volunteers ran a self-paced 1500 m on a track. On test days, a questionnaire (e.g., hydration and exercise habits etc.) was administered prior to the running event. Real-time heart rate (HR) of the students and environmental condition data were recorded. The collected data were then used to estimate core temperatures and physiological strain levels (PSL) using a two-node thermal model. **Results:** Although the WBGT was classified as safe to exercise, many students' HR increased to 200 bpm, and their PSL ranged from moderate to high, suggesting a significant risk for heat-related illness. The ER time was significantly associated with exercise habits of the students and WBGT. **Conclusions:** Current operations for ER tests in Japan need to be revisited to prevent heat illness and injury. Using both WBGT and thermal modeling improves understanding of the thermal status of runners and helps to mitigate the risk for heat illnesses.

Keywords: endurance running, Japanese physical education, thermal modeling, student survey

INTRODUCTION

The endurance running (ER) known as "Jikyu-sou" in Japanese is a common physical test used in physical education (PE) classes in Japanese middle and high schools. Based on Japanese school PE guidelines, once a year, students have to take a physical strength test that includes ER, hand grip strength, anteflexion, abdominal crunches, repeated side-to-side jump, and standing broad jump. In particular, the purpose of ER tests is to learn their own pace to finish running and measure aerobic endurance levels. The ultimate goal of the physical strength test is to understand physical strength and weakness and improve a fitness plan of each student (1). Typically, students are required to run up to 1500 m for boys and 1000 m for girls within a certain time. This requirement was introduced in 1949 and remains in place today (2).

Over the years, endurance running has become an unpopular exercise for students (3, 4). Although ER tests naturally increase exercise intensity, students tend to push themselves further to run faster by competing or keeping up with other students, resulting in feelings of exhaustion and not feeling well upon run completion. In addition, as a result of global warming, the incidence rate of high daily temperatures has increased, which may burden students' performance on ER tests. Consequently, endurance running is likely to induce heat related illness and to be categorized as a tough sport among students (5).

Because the incidence of high daily temperatures has led to an increase in heat related illness experienced more broadly in Japan to include schools (6), the Wet Bulb Globe Temperature (WBGT) index is used in order to perform endurance running tests in PE classes safely. The WBGT is a measurement to estimate the degrees of heat stress using outside environmental factors such as air temperature, humidity and radiation (7) and it is used as the school guideline. However, previous studies indicated that the locations or situations of how WBGT was measured may be susceptible to heat disorders (8, 9) and the sole usage of WBGT to determine heat strain of individuals is not fully sufficient. The individual factors of the human such as personal physiological parameters and life styles of individuals (e.g., the intensity and hours of physical exercises, sleeping hours, levels of dehydration, personal motivation for running) may also affect the likeliness of heat related illnesses.

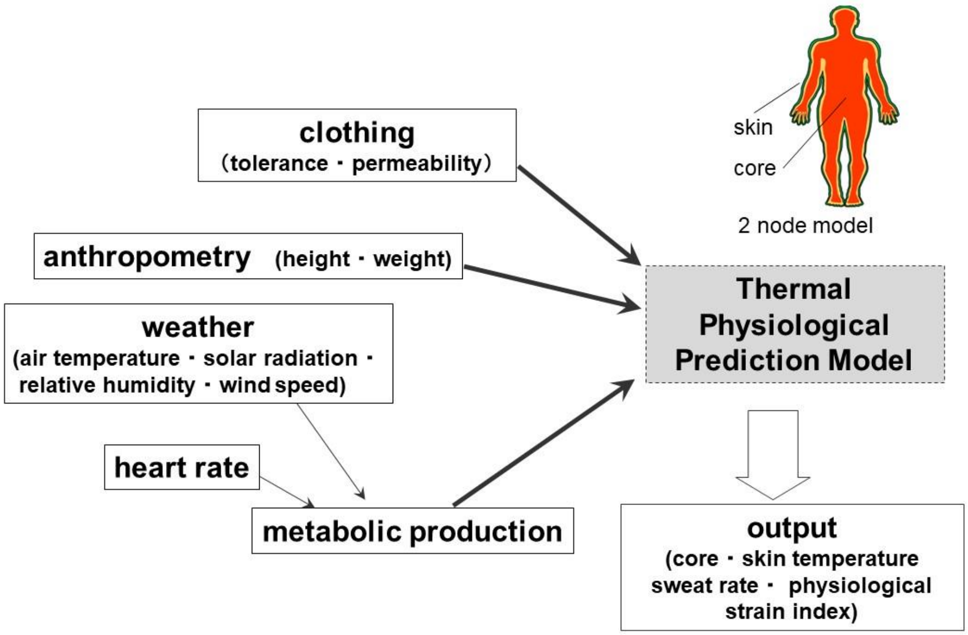
In this study, thermal strain levels of the Japanese KOSEN students during endurance running in PE classes were evaluated using the combination of a simple non-invasive thermal model (10,11), real-time physiological measures, and a student self-reported survey.

METHOD

The Two-Node Non-Invasive Thermal Model

The thermal model used in this study is a mathematical model where the human body is represented as a cylinder consisting of two compartments (core and skin) surrounded by a clothing layer. The model is very simple and requires only a few non-invasive input variables including the participant's anthropometric values (height, weight, and body mass index [BMI]), heart rates, environmental conditions (air temperature, relative humidity, mean radiant temperature, and wind speed), and biophysical properties of the clothing/equipment worn (total insulation, water vapor permeability). Then the model predicts core temperature (Tc) in a stepwise time (e.g., minutes, seconds). Figure 1 provides a schematic of the model. Detailed descriptions of this model are provided elsewhere (11,12) The model inputs characterize individuals that are used to determine energy flows between and within compartments, body temperatures, and physiological responses.

Figure 1. A non-invasive thermoregulatory model



The highlight of the model functions related to this study includes the heat production and physiological strain index (PSI) (13). A heat production (M in watts) of this model is derived from the measured heart rate (HR) and environment temperature (14). This equation was used because the parameters are minimally non-invasive measures and provide an overall good correlation between O^2 uptakes and HR (14,15). The M equation using HR and environmental temperature was described as follows:

$$M = [0.68 + 4.69(HRratio - 1) - 0.052(HRratio - 1)(Ta - 20)]58.1AD \quad [1]$$

where HRratio—observed HR given at the time/resting HR of the individual, and Ta—ambient temperature in °C, and AD is the body surface area (m^2). Cardiac output, indicated by HR, supplies blood and oxygen for metabolism and also provides blood flow to the skin for thermoregulation. For a given metabolic activity, the HR will increase with increasing environmental temperatures because of the thermoregulatory need for increased skin blood flow. The prediction of M shown in Eq. (1) was derived from HR and oxygen consumption measured over a range of metabolic activities and environmental temperatures (10,11). The calculated M is then used to predict Tc based on the heat balance and transfer equations (16,17).

The PSI is an internal thermal measure that was calculated based on measured HR and predicted Tc (10,11) by the model for evaluating on-line heat strain levels of individuals calculated as follows (13):

$$PSI = 5(Tc_t - Tc_0)(39.5 - Tc_0)^{-1} + 5(HR_t - HR_0) \cdot (180 - HR_0)^{-1}, \quad [2]$$

where Tc_0 and HR_0 are the initial Tc and HR, respectively. Tc*t* and HR*t* are taken at a given time t during the heat exposure (13). The PSI is also simple, easier to use, and feasible for different operational and environmental conditions (13). The PSI consists of 0–10 scale, classifying them into five thermal categorical states (no, little, low, moderate, high, very high). In this study, the estimated Tc based on the thermoregulatory model described above was used to calculate PSI in a step-wise fashion.

Volunteers and Procedures

A total of 61 male high school KOSEN students wearing T-shirts and shorts participated in an outdoor endurance running test during their PE classes in June or July. They ran 1500 m on a track at their own pace. This study was approved by the Ethics Committee of NIT (KOSEN) Hachinohe College. Prior to the study participation, the students and their parents gave their written informed consent. The consent form included the purpose, risks, and importance of the study. On test days, the students' heights, weights, initial body temperatures, and resting heart rates were recorded. Then the questionnaire asking about hours and intensity of sleep during the night before the running day, the hydration level on the running day, the duration and intensity of physical exercises per week etc. was administered prior to the running event. Real-time HR and environmental conditions (air temperature, relative humidity, wind speed, WBGT) were monitored during the tests. The collected data were used to estimate core temperatures (Tc) using a two-node thermal model described above (10,11). The estimated Tc was then used to calculate the students' PSI values (13). Figure 2 is the general procedure of the study.

Analyses

Descriptive analyses of physiological data (i.e., HR, Tc, and PSI) were conducted to evaluate physiological strains during the running according to WBGT levels. Since endurance running time is used as the Japanese PE guideline, it is considered as an indicator of physical fitness levels (18). A one-sample T-test (one tailed test) was conducted to compare if the running time of KOSEN students was slower than nation-wide high school time. In addition, the associations of running time with weekly exercise hours, PSI at the finish line, hydration levels on the running day, and WBGT were also examined using a linear regression analysis (19). The independent variables including the amount of exercise per week and WBGT were classified as categorical variables, while the hydration and PSI levels were treated as continuous variables.

RESULTS

Environmental Condition

Table 1 summarizes the environmental condition of each PE class on the running day. Based on the WBGT category (safe to exercise: < 21℃, exercise with caution: 21℃ ≦ WBGT< 25℃, warning: 25℃≦WBGT< 28℃), the overall WBGT measurements during the tests ranged between 18º and 28ºC which correspond to the safe or warning guideline.

Student Characteristics

Table 2 is the summary of the student characteristics. Compared to the national average endurance running time of the high school male students in Japan (Range: 6:01 and 6:5 minutes (361 and 387 seconds)) (20), the average running time of KOSEN students in this study was 7.2 minutes (433 seconds). A one sample T-Test indicated that the KOSEN students in this study took significantly more time to finish their endurance running event ($p<0.05$).

Figure 2. The study procedure

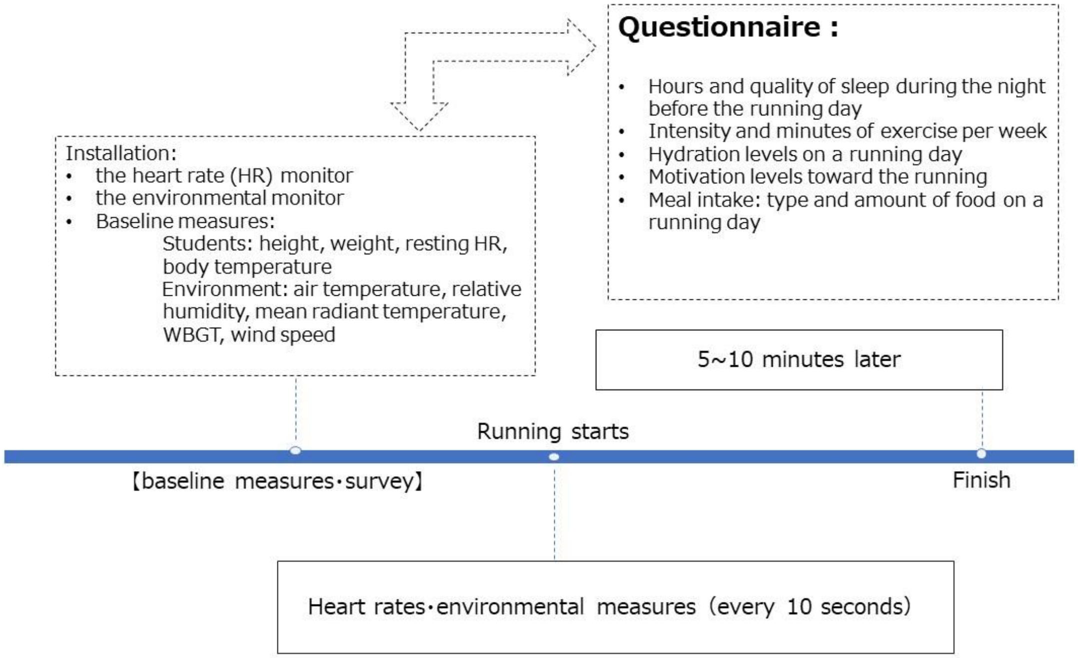


Table 1. The summary of the environmental condition on the running days

Environmental factor	*Mean ± Standard Deviation*
Air temperature (℃)	23.7±2.4
Relative humidity (%)	74.9±11.6
Wind speed (ms^{-1})	6.1±1.9
WBGT（heat index）*	23.1±2.9

Table 2. The summary of the students' characteristics by class.

Class/Characteristics	*Mean ± Standard deviation*
Age (yrs)	15.5±0.6
Height (cm)	169.7±4.8
Weight (kg)	60.9±10.7
Body Mass Index	21.2±3.6
Running time in minutes (seconds)	7.2±1.1 (433.3±65.9)

Comparison of Physiological Condition by WBGT Category

Figure 3a, b, and c show the mean HR, Tc, and PSI at the finish line by the WBGT categories, respectively. Regardless of the WBGT categories, mean HR and Tc at the finish line were close to 200 bpm and 38 ℃, respectively, indicating that the students were working close to their maximum capacity. Similarly, the mean PSI of runners at the finish line were more than 7.0, indicating that their strain levels were high, although WBGT indicated that it was safe to exercise.

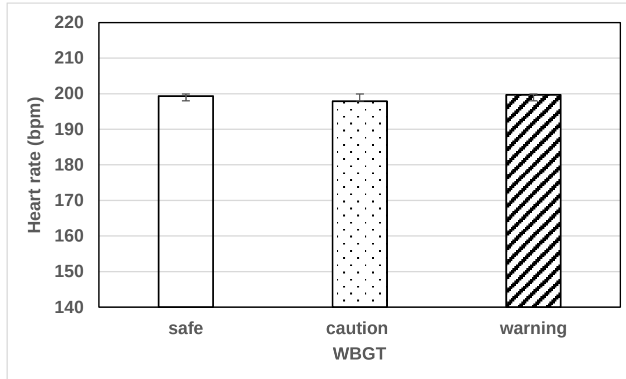
Table 3 shows the summary of the distribution of the PSI at the finish line by WBGT categories. Even though it was safe to exercise outside based on WBGT, almost 86% of the student PSIs were highly elevated.

Association between Running Time and Internal/External Factors

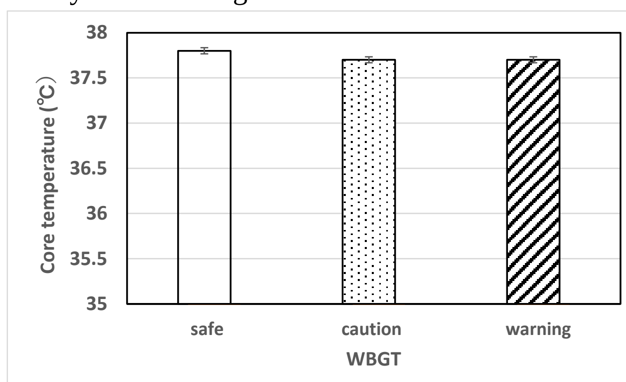
Table 4 shows the association of running time with the students' weekly exercise hours, PSI at the finish line, hydration levels on the running day, and WBGT was examined using a linear regression analysis. The students who self-reported the regular physical activities of more than 1000 minutes per week were likely to finish their running in a faster time ($p<0.05$). The running time was significantly longer when WBGT was in the warning heat stress zone, compared to WBGT as a safe zone ($p<0.05$). However, the running time did not show the statistical association with the students' water intakes prior to running and PSI levels at the finish line.

Figure 3. Physiological responses at the finish line by Wet Bulb Globe Temperature (WBGT) categories

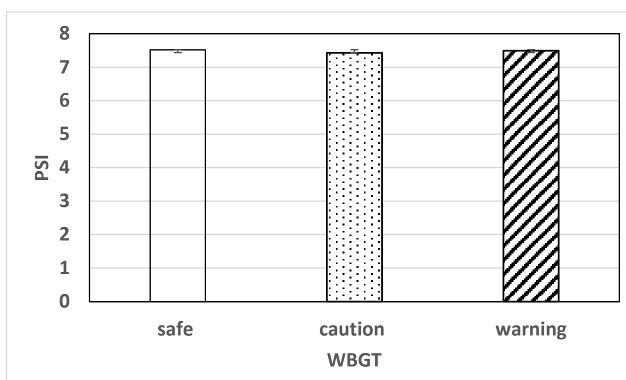
a. Mean heart rates (HR) at the finish line by WBGT categories



b. Mean core temperature (Tc) at the finish line by WBGT categories



c. Mean physiological strain index (PSI) at the finish line by WBGT categories



WBGT categories

safe < 21°C;

21°C ≦ caution < 25°C;

warning ≧ 25°C

Table 3. The association between Physiological Strain Index (PSI) at the finish line and Wet Bulb Globe Temperature (WBGT) categories.

PSI categories	*WBGT categories*		
n (%)	Safe < 21	21≦Caution< 25	25≦Warning < 28
Moderate (< 7.0)	3 (14.3)	8(26.7)	1 (10.0)
High (≧ 7.0)	18 (85.7)	22 (73.3)	9 (90.0)
Total	21 (100)	30 (100)	10 (100)

Table 4. The association between running time and internal/external factors

Source	**SS**	**Df**	**MS**
Model	93881.2746	6	15646.8791
Residual	167007.807	54	3092.73717
Total	260889.082	60	4348.15137

Number of observations = 61
F(6, 54) = 5.06
Prob > F = 0.0004
R-Squared = 0.3599
Adjusted R-Squared = 0.2987
Root MSE = 55.612

Running time	**Coefficients**	**Standard errors**	**T**	**P > |t|**
PSI at the finish line	-15.71969	13.76591	-1.14	0.259
Athlete				
1	-0.045732	27.77596	-0.00	0.999
2	-56.60355	15.88104	-3.33	0.002*
Hydration prior to run	-21.96824	11.41991	-1.92	0.060
WBGT				
1	12.95917	16.23572	0.80	0.428
2	69.16678	22.3158	3.10	0.003*
_cons	611.5072	109.7529	5.57	0.000

Notes: * indicates p < 0.05

athlete [0: 0-499 exercise minutes/week, 1: 500-999 minutes/week, 2: ≧1000 minutes/week]

WBGT [0: WBGT<21℃, 1: 21℃≦WBGT＜25℃, 2: 25℃≦WBGT]

DISCUSSION

The endurance running tests were conducted during the PE classes when environmental heat index ranged from the safe to cautious zones. Even though the WBGT was classified as safe to exercise, many students' HRs increased to maximum level (220-age), and their PSI levels at the finish line ranged from moderate to high, suggesting a significant risk for heat-related illnesses. As the previous studies have indicated, there was a direct relationship between HR and intensity of the exercise (21). The endurance running was a vigorous exercise for most of the students in this study and using a HR monitor was helpful to screen the safety of the students while running. In addition, using a non-invasive thermal model provides more information including predicted Tc and physiological strain levels of individuals, which is very convenient to use in the field.

The combined usage of a HR monitor and a thermal model is a common screening method in the US and European countries to understand the thermal safety of diverse populations including occupational workers and athletes (22 ,23, 24). Such a method is important not only for workers and athletes to realize their own physiological levels rather than solely relying on their perception levels but also for the instructors or management team to understand the thermal safety. In the similar manner, the approach in this study was applicable to identify the safety of students from both internal (physiological) and external (environmental) point of views during the PE classes. It is common that during Japanese PE classes, one PE teacher supervise 30-40 students simultaneously and school nurses stand by in the school infirmary. Under the current Japanese PE guideline (1), the length of ER was determined by sex and is not allowed to change based on environmental conditions. Thus, given the situations, we recommend using real-time HR monitor and implementing a thermal status watch in addition to teacher and nurse oversight. The use of a monitor and thermal modeling does not take the place of human oversight. However, it provides useful tools to aid students and teachers to make informed decisions on when to stop the endurance run.

Although it is not listed in the guideline, both PE teachers and students assume that runners won't drink water until they finish or drop out of ER tests since the tests have been conducted in this manner for long time in Japan. As global warming is a major issue and the incidence in heat-related illness has increased in Japan, it is important for PE instructors to revisit and adapt the test conditions on ER tests based on scientific facts. Allowing students to drink cold water or use of ice as needed is recommended during or after ER tests. In addition, in our school, an instructor introduces a 10 minute-run in every PE class for a month prior to ER tests to acclimate students to run at their own pace and to get used to running in hot conditions in summer months. In particular, many of the first-grade students, who have a history of not practicing physical activities in the past 3 months by spending lot of time for preparing for the nation-wide high school entrance exams, are likely to have a high risk of heat related illness during the first high school ER tests. Such "acclimation" training is very important to perform ER tests safely and prevent from heat related illness and we recommend that this practice continue.

This study also showed the students who finished endurance running earlier tended to spend many hours on sports per week. Higher WBGT also was significantly associated with longer running time. However, hydration levels prior to running and physiological strain levels at the finish line were not significantly associated with endurance running time. Previous studies examined the attitudes of students toward endurance running and found that motivation/engagement, achievement, collaboration, and likeness/dis-likeness are important factors that affected their running performance (4, 18, 25). Thus, measuring psychological factors such as motivation levels toward ER tests could be additional beneficial factors in the future study to identify running performance under heat and the likelihood of heat related illness.

Our KOSEN PE classes are currently held only once a week (total 90 minutes/week) due to many other engineering and general science classes while regular high schools have PE classes 2-3 times a week (total of 100~150 minutes/week) in average (26). Furthermore, the Japanese government held the behavioral restrictions due to COVID-19 pandemics for more than three years and such a long restriction increased the number of remote classes and limited physical exercise at home (27). The lack of physical activities potentially decreased the motivation levels of physical exercise and physical fitness. The fitness levels of Japanese students were also reported to be lower in 2021 than those prior to COVID time (20). Thus, educating the importance of physical exercise and enhancing regular exercise habits beyond PE classes such as club activities and local sports events is important to help students improve their stamina and endurance running without heat injury and illness, as well as motivate their goals.

Conflicts of interest. The authors certify that there are no conflicts of interest to report.

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