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EXPERIMENTAL STUDY ON GENDER DIFFERENCE IN MENTAL STRESS AND WALKING SPEED DURING TUNNEL FIRES

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ABSTRACT

To investigate the relationship between mental stress and walking speed in a smoke-filled tunnel, an evacuation experiment was conducted in a smoke-experience tent, where 16 students (8 males and 8 females) participated. The heart rate change rate before and during the experiment (Group 0: <1, Group 1: 1–1.2, Group 2: >1.2) was used as an index of mental stress. The mean walking speed in smoke of each group were calculated based on gender. At Cs = 0.5–1.0 m^{-1}, the mean walking speed values of the females of Groups 0, 1, and 2 were 0.72, 0.94, and 1.23 m/s, respectively. the mean walking speed gradually increased as the heart rate change rate increased. However, the mean walking speed values of the males of Groups 0, 1, and 2 were 1.05, 0.83, and 0.75 m/s, respectively. the mean walking speed gradually decreased as the heart rate change rate increased. This indicates that males and females possess different spatial cognitive styles, implying that the influence of mental burden on walking differs based on gender.

Keywords: tunnel fire, smoke, walking speed, mental stress, gender, experimental.

1. INTRODUCTION

When a fire occurs in a tunnel, people evacuate through smoke, and there is a substantial risk of human casualties. To minimize this risk, evacuation behavior in smoke-filled tunnels should be investigated. There are several evacuation behavior studies in smoke-filled tunnel like spaces [1–9].

However, there are few studies on mental stress-related evacuation behavior other than Jin [10] and Seike et al. [11]. Leach [12] reported that during ship and airplane disasters, 10%–20% of evacuees can act and decide calmly, whereas 70%–75% freeze and 10%–15% cry or scream. In addition, because of heart rate increasing and breathing difficulties due to acute stress reaction in the evacuation [13], the smooth evacuation is difficult. Therefore, it is necessary to consider mental stress in the evacuation. Jin [10] evaluated mental stress based on heart and breathing rates and reported that when people experienced mental stress caused by smoke, their walking speed slowed down. However, Jin's experiment was conducted over 40 years ago, and mental stress and walking speed had not been measured at the same time. Additionally, the gender differences had not been investigated.

Seike et al. [11] evaluated mental stress based on the heart rate and blood pressure, and reported that when the participants felt mental stress owing to the loss of visibility caused by wearing an eye mask, their walking speed slowed by 0.1 m/s. However, Seike et al. [11] did not consider smoke and the gender differences. Therefore, to investigate the relationship between mental stress and walking speed in smoke-filled tunnels, and differences in this relationship based on gender, we conducted a smoke evacuation experiment.

This paper focused on the gender behavior difference in the case of individual evacuation for the fundamental data to expand group dynamics based on this data in the future topic.

2. METHODOLOGY

2.1. Smoke experience tent

The experiment was conducted in a smoke-experience tent (tent, Figure 1). The length, width, and height of the tent were 10, 2, and 2 m, respectively. Four checkpoints (CPs) were set up inside the tent (Figure 2). The longitudinal and vertical directions were indicated by x and y, respectively, and the origin was set at CP1. For smoke density, three smoke density measurements were used to calculate the intensity of the incident light and the intensity of light passing through the smoke. Then, the following Lambert–Beer law was used to convert these values into smoke density:

$$Cs = \frac{1}{l} ln \frac{I_0}{I}$$

Where Cs is the smoke density, I_0 is the intensity of the incident light, I is the intensity of light passing through the smoke, and l is the light path length (l= 0.8 m).

Figure 1: Inside (left) and outside (right) the smoke tent

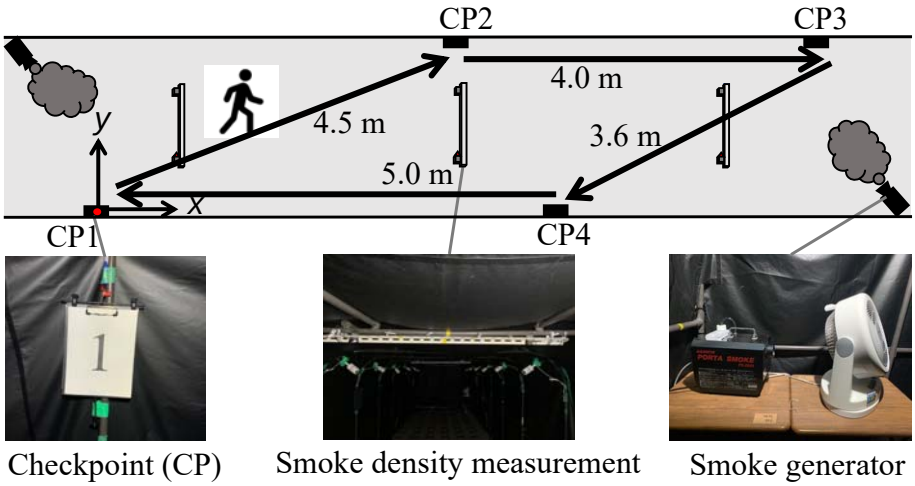


Figure 2: Evacuation route

2.2. Scenario

Participants were asked to evacuate by passing through CP1, CP2, CP3, CP4, and CP1. The evacuation route includes two paths along the wall (CP2–CP3, and CP4–CP1) and two diagonal paths (CP1–CP2, and CP3–CP4). To confirm the fundamental data of mental stress and walking speed under the smoke condition, this study focused on the paths along the wall. Each participant was asked to participate in five experiments with different smoke densities (Cs = 0–2.35 m^{-1}). Before the experiment, the participants were given an instruction, as stated below:

"A fire occurred in the tunnel, and the space became completely dark filled with smoke, therefore, please evacuate on an urgent basis."

2.3. Heart rate measurement

Ettema et al. [14] reported that heart rate is influenced by sympathetic and parasympathetic nerves and increases during mental stress load. Therefore, this study evaluated mental stress using heart rate variability as an index. Heart rate was measured in the experiment using Wahoo Tickr WF124 (arm-wound activity meter).

2.4. Participants

Sixteen students participated in the experiment (eight males and eight females). The age of the males ranged from 21 to 25 (mean age of 23 years), and the age of the females ranged from 20 to 23 (mean age of 21.4 years). The participants were instructed to wear a safety vest, a helmet, a mask, and knee and elbow pads and carry a stopwatch during the experiment. In addition, they were instructed to carry flashlights, referring to news [15, 16] that evacuees used the light of their cell phones during tunnel fire accidents.

3. RESULTS

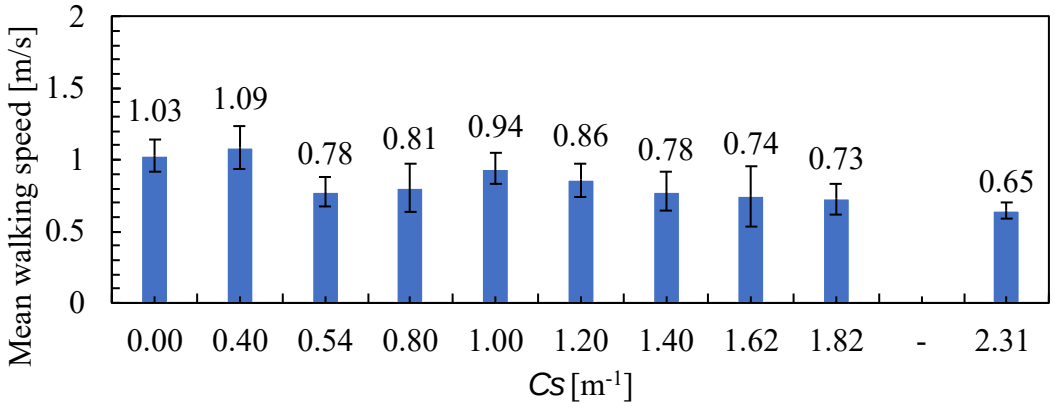
3.1. Walking speed

To investigate the walking speed under the smoke condition and its differences based on gender, the mean walking speed was calculated considering a smoke density increment of 0.2 m^{-1} starting from 0 (i.e., 0, 0.3–0.5, and 0.5–0.7 m^{-1}) (Figure 3). The horizontal and vertical axes corresponded to *Cs* and mean walking speed, respectively. The error bars corresponded to 95% confidence intervals. And the smoke density levelling was determined in this section.

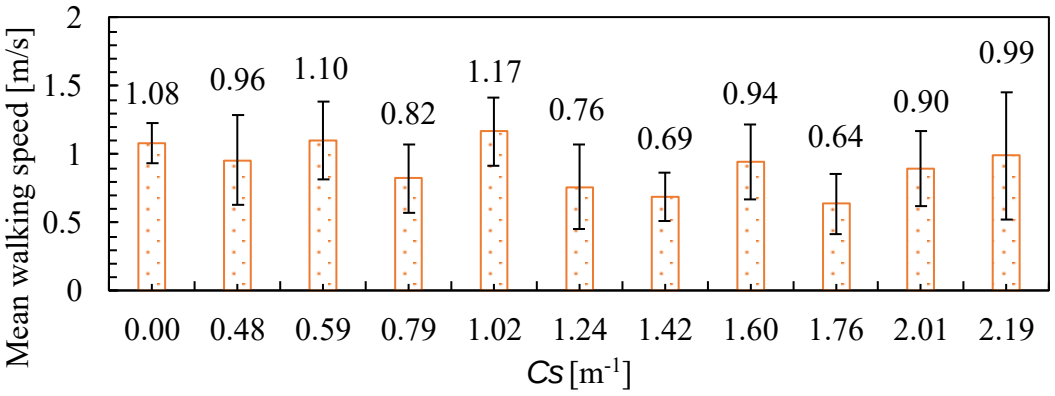
For males (Figure 3(i)), the mean walking speeds were 1.03 and 1.09 m/s at 0 and 0.40 m^{-1}, respectively. the mean walking speed at 0.4 m^{-1} was faster than that at 0 m^{-1}. From 0.50 to 1.00 m^{-1}, the mean walking speeds decreased to <1 m/s but tended to gradually increase. After 1.00 m^{-1}, the mean walking speed gradually decreased, and after 1.40 m^{-1}, the mean walking speed decreased to <0.8 m/s. There were no participants at 1.9–2.1 m^{-1}. For females (Figure 3(ii)), the mean walking speeds were 1.08 m/s at 0 m^{-1}, and 0.96 m/s at 0.48 m^{-1}, which was slower than that at 0 m^{-1} and decreased to <1 m/s. After 0.50 m^{-1}, the mean walking speed was 0.82 m/s at 0.79 m^{-1}, which was less than 0.9 m/s. After 1.00 m^{-1}, the mean walking speed was 0.76 m/s at 1.24 m^{-1}, which was less than 0.8 m/s. However, the mean walking speeds at 0.59 and 1.02 m^{-1} were faster than that at 0 m^{-1} as the error bars were larger, ranging from 0.82 to 1.38 m/s and 0.91 to 1.42 m/s, and the sample sizes were small (9 and 10, respectively), suggesting that the mean walking speeds were influenced by the faster participants. Moreover, after 1.40 m^{-1}, the mean walking speeds were 0.69 m/s at 1.42 m^{-1} and 0.64 m/s at 1.74 m^{-1}, which were less than 0.7 m/s. However, the mean walking speeds were faster than 0.9 m/s at 1.60, 2.01, and 2.19 m^{-1} owing to the smaller number of samples (9, 4, and 4, respectively) and larger error bar ranges (0.67–1.22, 0.69–1.17, and 0.52–1.46 m/s, respectively).

In summary, for the males, except for 0.40 m^{-1}, the mean walking speeds at all the smoke densities were slower than that at 0 m^{-1}. From 0.50–1.00 m^{-1}, the mean walking speeds tended to increase. From 1.00–1.40 m^{-1}, the mean walking speeds gradually decreased. After 1.40 m^{-1}, the mean walking speeds decreased to <0.8 m/s. For females, except for 0.59 and 1.02 m^{-1}, the mean walking speeds at all the smoke densities were slower than that at 0 m^{-1}. From 0–0.50 m^{-1}, the mean walking speed decreased to <1 m/s. From 0.50–1.00 m^{-1}, the mean walking speed decreased to <0.9 m/s. From 1.00–1.40 m^{-1}, the mean walking speed decreased to <0.8 m/s. From 1.40–1.76 m^{-1}, the mean walking speeds decreased to <0.7 m/s. And after 1.76 m^{-1}, the mean walking speeds increased. It was found that the walking speeds of males and females under the smoke condition were different. However, the mean walking speeds of the males and

females changed at 0.50, 1.00, and 1.40 m^{-1}. Therefore, we classified the smoke density into five *Cs* levels, L0 (Level 0) (0 m^{-1}, no smoke), L1 (0–0.50 m^{-1}), L2 (0.50–1.00 m^{-1}), L3 (1.00–1.50 m^{-1}) and L4 (over 1.50 m^{-1}).



(i) Male



(ii) Female

Figure 3: Mean walking speed at 0.2 m^{-1}

3.2. Heart rate

To investigate the mental stress under the smoke condition and its differences based on gender, the heart rate change rate (the ratio of the heart rate before the experiment to the mean heart rate under the smoke condition during the experiment) was calculated as an index of mental stress. We calculated the mean heart rate change rate of the participants whose heart rate increased during the experiment based on the gender and *Cs* level (Figure 4). The horizontal and vertical axes correspond to the *Cs* level and mean heart rate change rate, respectively. The error bars correspond to 95% confidence intervals. As the participants were nervous and anxious about the experiment before the start of the first experiment, the heart rate before the experiment was used as the mean heart rate for 3 minutes before the start of the second experiment.

The mean heart rate change rates of the males were 1.23 at L0, 1.22 at L1, 1.24 at L2, 1.15 at L3, and 1.11 at L4. The mean heart rate change rates of the females were 1.22 at L0, 1.26 at L1, 1.19 at L2, 1.10 at L3, and 1.15 at L4. At L0, the difference between the mean heart rate change rates of the males and females was almost equal at 0.01. However, at L2 and L3, the mean heart

rate change rates of the males were larger than those of the females. The reason for this is that, as reported by Sandstrom et al. [17], when recognizing space, males are characterized using the entire spatial image, whereas females are characterized using familiar objects in space as landmarks. Therefore, the males had difficulty grasping the whole spatial image because of less visibility under the smoke condition, whereas the females used checkpoints or something else as landmarks and were able to recognize space more easily than males, which may have resulted in less mental stress. In contrast, at L1 and L4, the heart rate change rates of females were larger. The reason for this is that the smoke became denser at L4, making it difficult for participants to recognize the space, even for females. As the males may have become slightly accustomed to the smoke-filled tent, the females may feel more mental stress than the males. Meanwhile, the heart rate change rate of females at L1 was larger because the error bar ranges of the 95% confidence intervals were larger for the males (1.08–1.36) and females (1.16–1.37), and the samples were smaller (5 and 5, respectively).

The mean values of heart rate change rate of males and females were almost equal at L0, whereas the mean values of males were larger than the females at L2 and L3. But the mean value of females was larger than the males at L4.

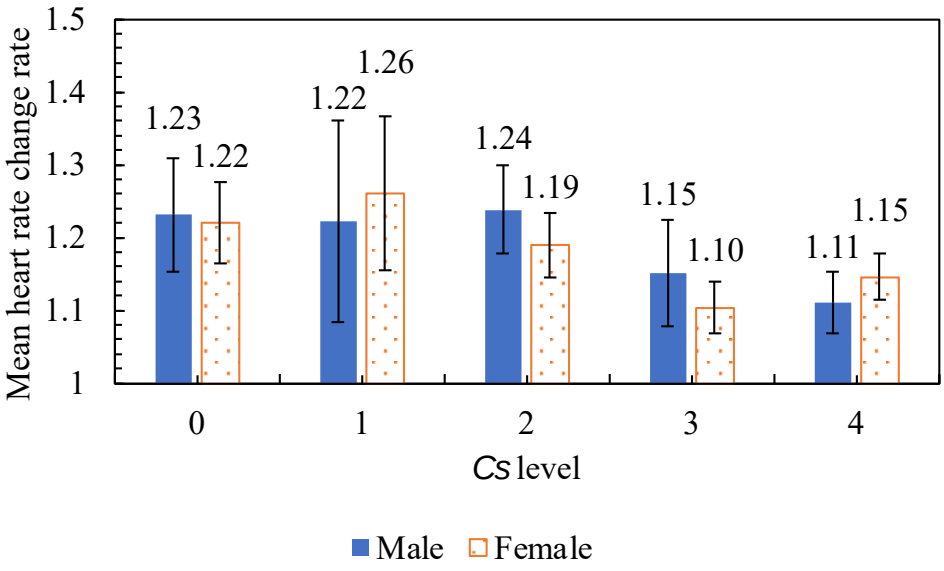


Figure 4: Mean heart rate change rate before and during the experiment

3.3. Heart rate and walking speed

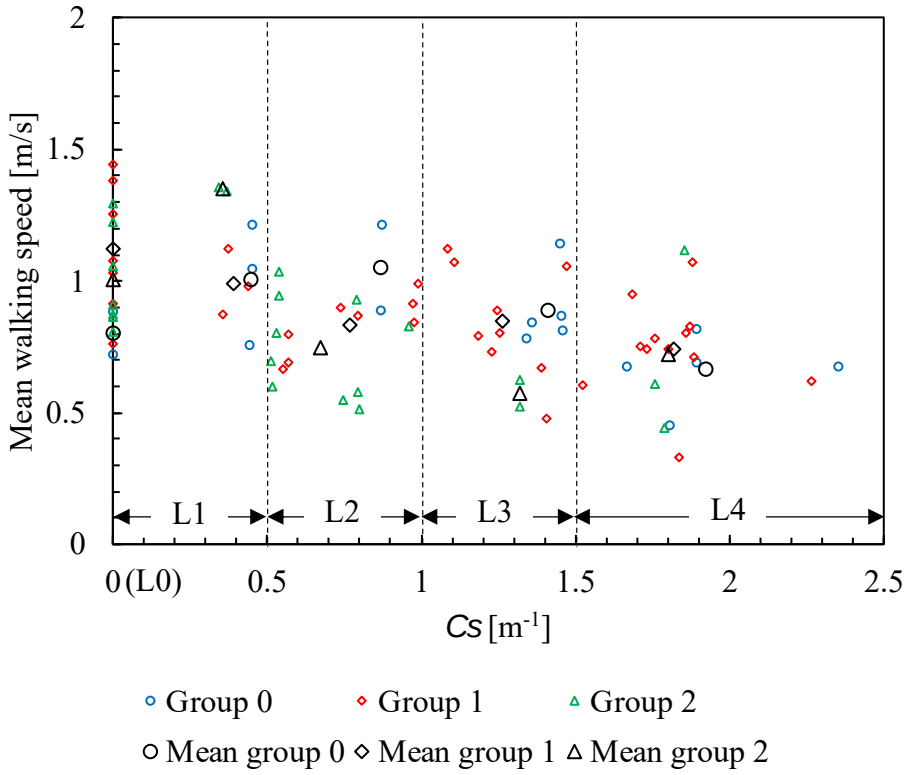
To investigate the relationship between mental stress (heart rate change rate) and walking speed under the smoke condition and the differences in this relationship based on gender, we classified heart rate change rate into three groups (Group 0: <1, Group 1: 1–1.2, Group 2: >1.2). To divide Groups 1 and 2 using a heart rate change rate of 1.2, Whitley et al [10] conducted a walking experiment on 12 female students and found that the heart rate after walking for 50 s at 3.31 km/h (0.92 m/s) increased by ~1.19 times, compared with that before walking. Therefore, this study referred to the results of Whitley et al. [18] and classified mental stress into groups. We investigated the distribution and mean values of the walking speed of each group based on the gender and *Cs* level (Figure 5). The horizontal and vertical axes correspond to the *Cs* and mean walking speed, respectively. Groups 0, 1, and 2 are denoted by circles, rhombuses, and triangles, respectively. The filled plots correspond to the mean values.

For the males (Figure 5(i)), the walking speed changed by 0.33–1.44 m/s at 0–2.35 m^{-1}. For the females (Figure 5(ii)), the walking speed changed by 0.19–1.89 m/s at 0–2.24 m^{-1}. The females

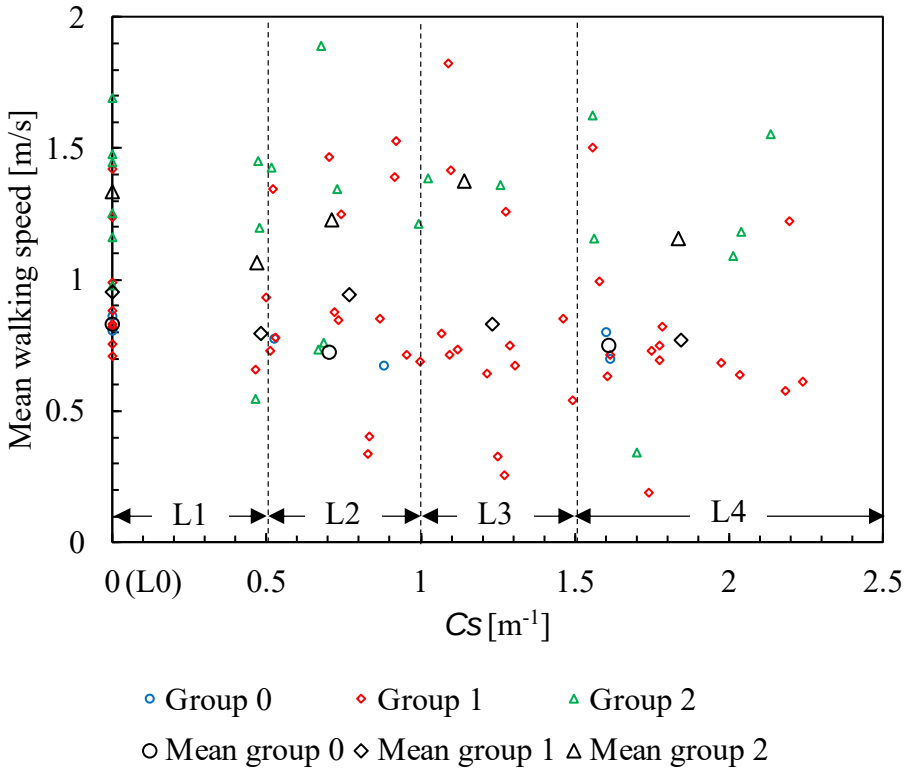
exhibited a larger difference between the maximum and minimum walking speeds than the males. Moreover, as all the participants whose walking speed exceeded 1.5 m/s were females, it was found that most females walked faster than the males owing to the difference in the spatial cognitive characteristics between males and females reported by Sandstrom et al. [17].

For the females, at L0, the mean walking speeds of Groups 0, 1, and 2 were 0.83, 0.96, and 1.33 m/s, respectively. The mean walking speed increased as the heart rate change rate increased, and a similar tendency was observed under the smoke condition. There were no Group 0 participants at L1 and L3. For the males, at L0, the mean walking speeds of Groups 0, 1, and 2 were 0.80, 1.12, and 1.00 m/s, respectively. However, at L1, the mean walking speeds of Groups 0, 1, and 2 were 1.01, 0.99, and 1.35 m/s, respectively. This tendency was similar to that observed for the females. At L2, the mean walking speeds of Groups 0, 1, and 2 were 1.05, 0.83, and 0.75 m/s, respectively. At L3, the mean walking speeds of Groups 0, 1, and 2 were 0.89, 0.85, and 0.57 m/s, respectively, which is in contrast with the females. The mean walking speed decreased as the heart rate change rate increased. At L4, the tendency was similar to that observed at L0.

For the females, the mean walking speed increased as the heart rate change rate increased, regardless of the smoke and *Cs* levels. For the males, the mean walking speed decreased as the heart rate change rate increased at L2 and L3. It was speculated that the walking speeds of the males and females varied when they experienced mental stress caused by smoke. As reported by Su et al. [19], under mental stress, males tend to take risks, whereas females tend to avoid risks. Therefore, it is considered that the walking speeds of the females were different from those of the males because the females had a stronger desire to escape faster from smoke than the males under the mental stress load.



(i) Male



(ii) Female

Figure 5: Walking speed at each group based on the *Cs* level

4. CONCLUSIONS

To investigate the relationship between mental stress (heart rate change rate) and walking speed in a smoke-filled tunnel (*Cs* = 0–2.35 m^{-1}), an evacuation experiment was conducted in a smoke-experience tent, where 16 students aged 20–25 (8 males and 8 females) participated. The results of the present study are summarized as follows:

- Regarding the heart rate change rate, compared with the females, the mean values with regard to the males were almost equal at 0 m^{-1} but larger at 0.50–1.50 m^{-1}. However, at >1.50 m^{-1}, the mean values of females were larger.
- With regard to the relationship between the heart rate change rate and walking speed, for the females, the mean walking speed increased as the heart rate change rate increased under the no-smoke and smoke conditions. For the males, the tendency was similar to that of the females at 0–0.50 m^{-1}, whereas the tendency was opposite for the females at 0.50–1.50 m^{-1}, where the mean walking speed decreased as the heart rate change rate increased.

5. ACKNOWLEDGMENTS

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