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Insights from an Experiment Investigating the Relationship between the Effect of Electrical Stimulation of the Ankle Tendons and the User's Biological Structure, Gender, or Age

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Abstract

The effects of transcutaneous electrical nerve stimulation (TENS) have individual differences in sensory presentation. These differences may stem from variations in the user's biological structure, including body size and skin conditions. In particular, TENS of the lower limbs is assumed to be affected by the differences in biological structure because the muscles of the lower limbs are larger than the muscles of the upper limbs, and a certain number of people have more hair on their skin than those of the upper limbs. Identifying the factors that explain these individual differences in TENS is crucial for evaluating the potential applications of TENS and developing appropriate research protocols in the future. In this study, we examined the individual differences in the effects of TENS by focusing on tendon electrical stimulation of the ankle, a method that presents body tilt sensations. Specifically, we investigated the correlation between the body tilt sensations and demographic (age, gender) or biostructure metrics (body weight, body fat percentage, etc.) in 28 experimental participants. The results revealed significant differences in the correct answer rate and the magnitude of body tilt sensations based on gender. Furthermore, there was a correlation between the correct answer rate or magnitude and the age of female participants at specific stimulation intensities. No biostructure metrics in this study were sufficiently correlated with the correct answer rate or magnitude of body tilt sensations.

CCS Concepts

• ***Human-centered computing*** → *Virtual reality; Mixed / augmented reality;* ***Haptic devices;***

1. Introduction

Transcutaneous electrical nerve stimulation (TENS) is a sensory presentation method used in the fields of virtual reality (VR) and augmented reality (AR). TENS can modulate various sensations such as taste [NM11, ASS*17], smell [MANA23], tactile [Kaj12, RKVM24], and force sensations [TTK19] by applying electric current through electrodes placed on the skin. TENS forms current density distribution between the electrodes and stimulates the internal body tissues.

However, when TENS targets the internal body tissues, desired sensations may not be appropriately presented to some users. This may be due to individual differences in pain perception and biological structure. Individual differences in pain perception complicate the setting of electrical stimulation intensity. TENS may cause discomfort such as a tingling sensation on their skin by stimulating relatively thin nerves related to pain perception [Kaj16]. To suppress the discomfort, experimental participants themselves adjust the current value to a level that does not cause tingling discomfort before the experiment in some experiments of TENS [TAN*22, OMA*24]. However, this method requires time and effort to adjust the intensity of the electrical stimulation for each user. Furthermore, this method can not present sensation to users who report a tingling discomfort at a lower value than that required for sensory presentation because it relies on the assumption that the current required for sensory presentation is below the current that causes the discomfort.

Individual differences in biological structure make it difficult to place electrodes at sites where external observation alone can adequately stimulate internal body tissues. For example, TENS of nerve bundles [FBS*15], which presents tactile sensations in the area innervated by the nerve by stimulating the nerve bundles, is expected to be influenced by the individual differences in biological structures. Anatomical studies have reported significant individual differences in the arrangement of nerves [AZLB97, OKT*05], making it difficult to efficiently stimulate only the desired nerve in TENS of nerve bundles. To solve this problem, a method to automatically optimize the stimulation sites of muscle electrical stimulation using multiple electrodes arranged in an array has been proposed [MWS*23]. Although this method can be applied to muscle electrical stimulation where the effect of electrical stimulation can

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be observed externally as muscle activity, it is not applicable to the TENS in which the effectiveness can not be observed externally, such as tactile presentation by nerve bundle electrical stimulation. Furthermore, regarding TENS of the lower limb, even if the stimulation site is optimized for nerve bundle electrical stimulation or tendon electrical stimulation of the lower limb, the target tissue may not be stimulated due to inhibition by other tissues such as muscle or fat. This is because the tissue of the lower limb is larger, as its surface area is twice as large as that of the upper limb [Wal51]. In addition, a certain number of people have more hair remaining in the lower limbs than in the upper limbs. Thus, individual differences in biological structure are considered to be one of the most critical factors affecting the effectiveness of TENS.

Therefore, it is important to investigate the individual differences in biological structure, especially with regard to TENS of the lower limbs. Previously, a large-scale research investigated the relationships between gender or age and perception thresholds against TENS of the upper and lower limbs [SKK*11]. However, this study did not scope to evaluate individual differences in TENS as a sensory display that presents tactile or force sensations by applying a current greater than the perception threshold. In order to evaluate the potential of the sensory display using TENS and to formulate appropriate experimental protocols, it is necessary to investigate individual differences in sensory presentation using TENS at current values greater than the perception threshold. Therefore, we investigated the individual differences in the effects of TENS by focusing on tendon electrical stimulation of the ankle (ankle TES), a method that presents body tilt sensations [TAN*22]. Specifically, we investigated the correlation between the body tilt sensations and demographic metrics (age, gender) as well as biostructure metrics (body weight, body fat percentage, etc.).

2. Experiment

To investigate the relationships between the body tilt sensations induced by ankle TES and demographic (age, gender) or biostructure (body weight, body fat percentage, etc.) metrics, we conducted an experiment in 28 participants. This experiment was approved by the ethical review board in the University of Tokyo.

2.1. Hypothesis

We formulated the following two hypotheses:

H1 There may be a correlation between the effects of ankle TES and age or gender.

H2 There may be a correlation between the effects of ankle TES and body weight, body fat percentage, body muscle percentage, length of the ankle circumference, or presence of ankle hair.

2.2. Procedure

First, the experimental participants were informed about the experiment and signed a consent form. Participants completed a questionnaire regarding demographic metrics (age and gender) and experience using TENS. Participants then recorded their body weight, body fat percentage, body muscle percentage, skin moisture level (front side, back side, inside and outside of the right ankles), length of the ankle circumference, and presence of ankle hair. Participants used a body scale (Omron, KRD-703T) to measure body weight and body fat percentage and a skin checker (Shenzhen Jiatu Co., Ltd.) to measure ankle skin moisture level. Length of ankle circumference was measured by the experimenter using a tape measure. The presence or absence of ankle hair was assessed visually by the experimenter and categorized into two values: with hair or without hair.

Figure 1: *(a) An experimental participant performing the trial. (b) Electrodes placed on the participant's ankles.*

Next, participants attached an electrical stimulator to their ankles and performed experimental trials as shown in Figure 1. In each trial, a 5-second electrical stimulation, the same duration as that in the previous study on ankle TES [TAN*22], was applied. Then, participants answered the following four questions about their experience of electrical stimulation using a numeric keypad.

Q1 To what extent did you feel a lateral body tilt sensation during the electrical stimulation? (1: as much as 10 degrees downhill to the left, 4: no lateral body tilt sensation, 7: as much as 10 degrees downhill to the right)

Q2 To what extent did you feel an anteroposterior body tilt sensation during the electrical stimulation? (1: as much as 10 degrees downhill to the forward, 4: no anteroposterior body tilt sensation, 7: as much as 10 degrees downhill to the backward)

Q3 How confident are you in your answers to the former two questions? (1: not at all confident, 7: very confident)

A 10-degree slope was prepared so that participants could check the extent of the 10-degree incline at any time. If strong discomfort due to electrical stimulation occurred during each trial, the trial could be skipped by pressing the forced termination button. After participants completed all trials, they removed the electrical stimulator and answered to an interview. Finally, they received Amazon gift card worth 3,000 JPY as a compensation.

2.3. Conditions and iterations

In this experiment, six stimulation site conditions and two stimulation intensity conditions were adopted. Two trials were conducted

Table 1: *Stimulation site for each electrical stimulation condition. TA, AC, PL, FDL denote the tibialis anterior muscle, Achilles, peroneus digitorum longus, and flexor digitorum longus tendons, respectively.*

Condition	Stimulation site of the left ankle	Stimulation site of the right ankle
FS	Frontside (TA tendon)	Frontside (TA tendon)
BS	Backside (AC tendon)	Backside (AC tendon)
LS	Outside (PL tendon)	Inside (FDL tendon)
RS	Inside (FDL tendon)	Outside (PL tendon)
SHAM	Inside (PL tendon)	Inside (PL tendon)
NONE	None	None

for each combination of the stimulation site and stimulation intensity conditions for a total of 24 trials ($= 6 \times 2 \times 2$). The six stimulation site conditions were FS, BS, LS, RS, NONE, and SHAM. The electrode placement for each condition is shown in Table 1. The FS, BS, LS, and RS conditions are devised in previous studies on ankle TES [TAN*22]. The FS condition induces backward body tilt sensation and center of pressure (CoP) shift. The BS condition induces forward body tilt sensation and CoP shift. The LS condition induces rightward body tilt sensation and CoP shift. The NONE and SHAM conditions are baseline conditions; in the NONE condition, no electrical stimulation is applied, and in the SHAM condition, current is applied to the peroneus longus muscle tendons of both feet.

The stimulation intensity conditions are 1.5 mA and 2.5 mA. In this study, we used these fixed electrical stimulation intensities to evaluate the effects of ankle TES at a consistent stimulation intensity among participants. Since the minimum average value of the stimulation intensity was approximately 2.5 mA in a previous study that employed a procedure to adjust the current value to the maximum value at which the participants did not feel strong discomfort [OMA*24], the values of 1.5 mA and 2.5 mA were determined so as not to exceed this value.

2.4. Setups

The electrical stimulators used an in-house current control circuit, which is said to be capable of stimulating target tissues at a constant intensity because it outputs a constant current regardless of body resistance [Kaj16], and the maximum current was limited to 4.0 mA. The electrical stimulators output bipolar square waves at 80 Hz, following the previous study [TAN*22]. We used disposable electrodes (3M Red Dot) with an adhesive area of $2.0cm \times 2.0cm$.

2.5. Participants recruitment and evaluation materials

To alleviate bias in the participants' age and gender, we recruited five or six participants for each combination of gender (male and female) and age (20 to 29 years old, 30 to 39 years old, and 40 years old or older) groups.

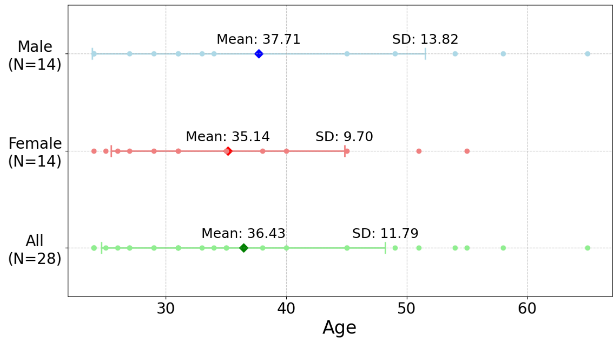

Figure 2: *Age distribution of the experimental participants.*

In this experiment, three types of information were obtained from the participants: demographic information (age and gender), biostructure information (body weight, body fat percentage, body muscle percentage, length of the ankle circumference, skin moisture level, and presence of ankle hair), and evaluations of body tilt sensation induced by ankle TES based on responses to Q1 through Q3. Demographic and biostructure information were collected once per participant. The evaluation of body tilt sensation was recorded for each trial.

2.6. Results

Figure 2 describes the age distribution of the experimental participants. The study included 28 participants, consisting of 14 males (mean age: 37.71 years, standard deviation: 13.82) and 14 females (mean age: 35.14 years, standard deviation: 9.70). Two participants frequently experience TENS, 17 have experienced it several times, and 9 have never experienced it.

Figure 3 illustrates the distribution of the evaluation values of body tilt sensation (responses to Q1 and Q2) and the confidence level of the evaluation (response to Q3) in each electrical stimulation condition. These results indicated that the anteroposterior body tilt sensation (Q2) was biased backward in the FS condition and forward in the BS condition. Similarly, the lateral body tilt sensation (Q1) was biased rightward in the LS condition and leftward in the RS condition. Essentially, it was confirmed that ankle TES induced the body tilt sensations in the direction opposite to the stimulated tendon, consistent with the previous study [TAN*22]. In the SHAM and NONE conditions, there was no directional bias in the responses to Q1 and Q2, indicating that the SHAM condition does not induce body tilt sensations in any specific direction.

Figure 4 illustrates the correct answer rate of the body tilt sensation for each demographic or biostructure metric. The correct answer rate was calculated as follows: (1) The total number of trials excluding the SHAM condition was counted. (2) The number of trials where participants correctly answered the direction of body tilt sensation was counted. (3) The correct answer rate was calculated by dividing the number from (2) by the number from (1). The criteria for determining the correct direction of body tilt sensation

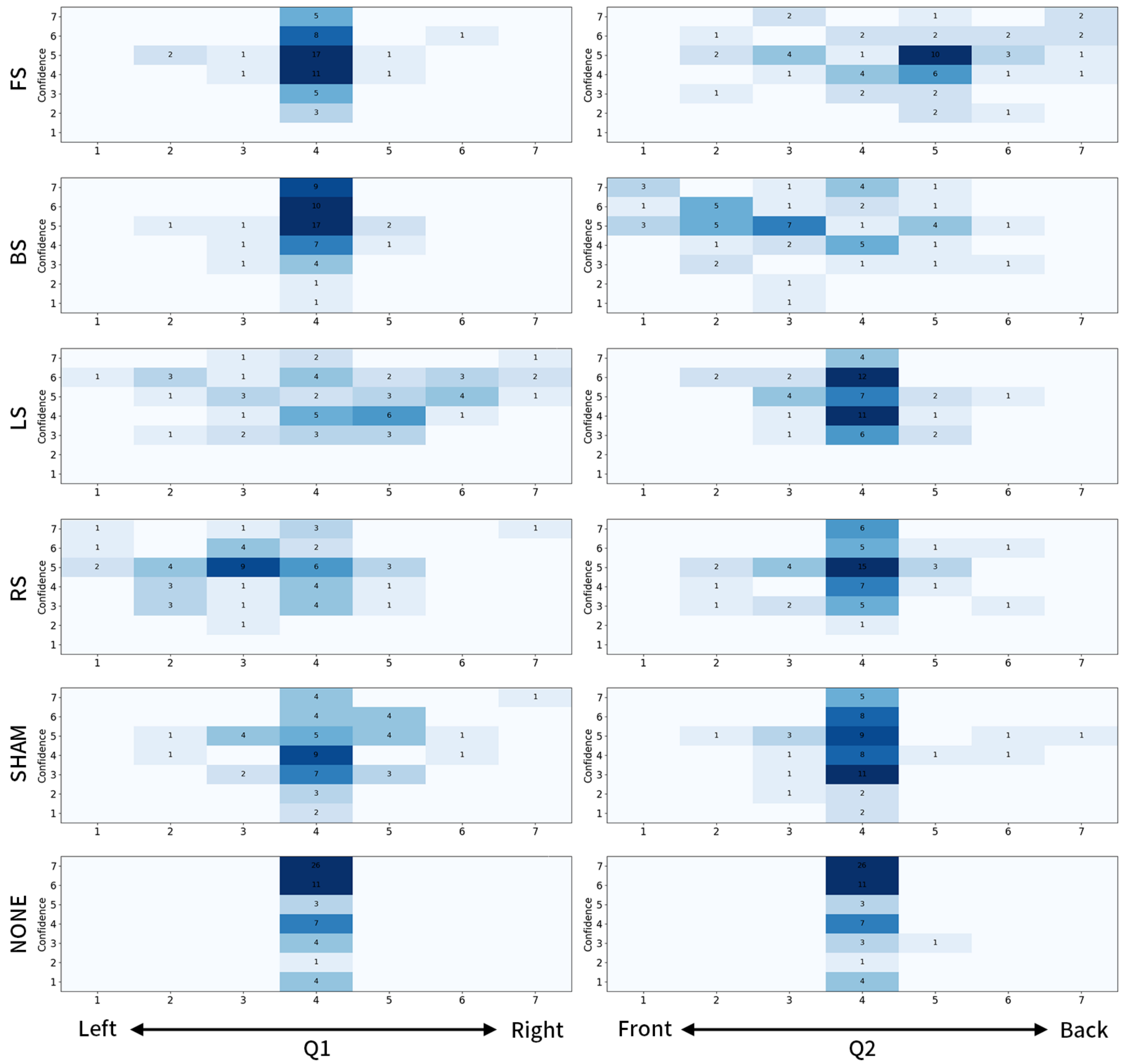

Figure 3: *Distributions of the evaluation of the body tilt sensation and confidence level in each electrical stimulation condition. The horizontal axis of the left distribution chart is the evaluation value of the lateral body tilt sensation (answers to Q1). The horizontal axis of the right distribution chart is the evaluation value of the anteroposterior body tilt sensation (answers to Q2). The vertical axis of the distribution chart is the confidence level of the evaluation (answers to Q3). The blue color is deeper for the evaluation value, where it is more frequently answered.*

in step (2) were as follows: the response to Q2 was 5 or more (5, 6, or 7) in the FS condition; the response to Q2 was 3 or less (1, 2, or 3) in the BS condition; the response to Q1 was 5 or more in the LS condition; the response to Q1 was 3 or less in the RS condition; and the response to Q1 and Q2 was 4 in the NONE condition.

In this study, we judged a correlation coefficient greater than 0.5 as a sufficient correlation and conducted comparison tests with a significance level of $\alpha = 0.05$. Figure 4 (a) illustrates the correlation between the correct answer rate and the age at the stimulation intensity of 1.5 mA. It indicates a correlation for the female data ($r = -0.59$). Figure 4 (b) illustrates the correlation between the correct answer rate and age at the stimulation intensity of 2.5 mA. It indicates no correlation for both male and female data. Fig-

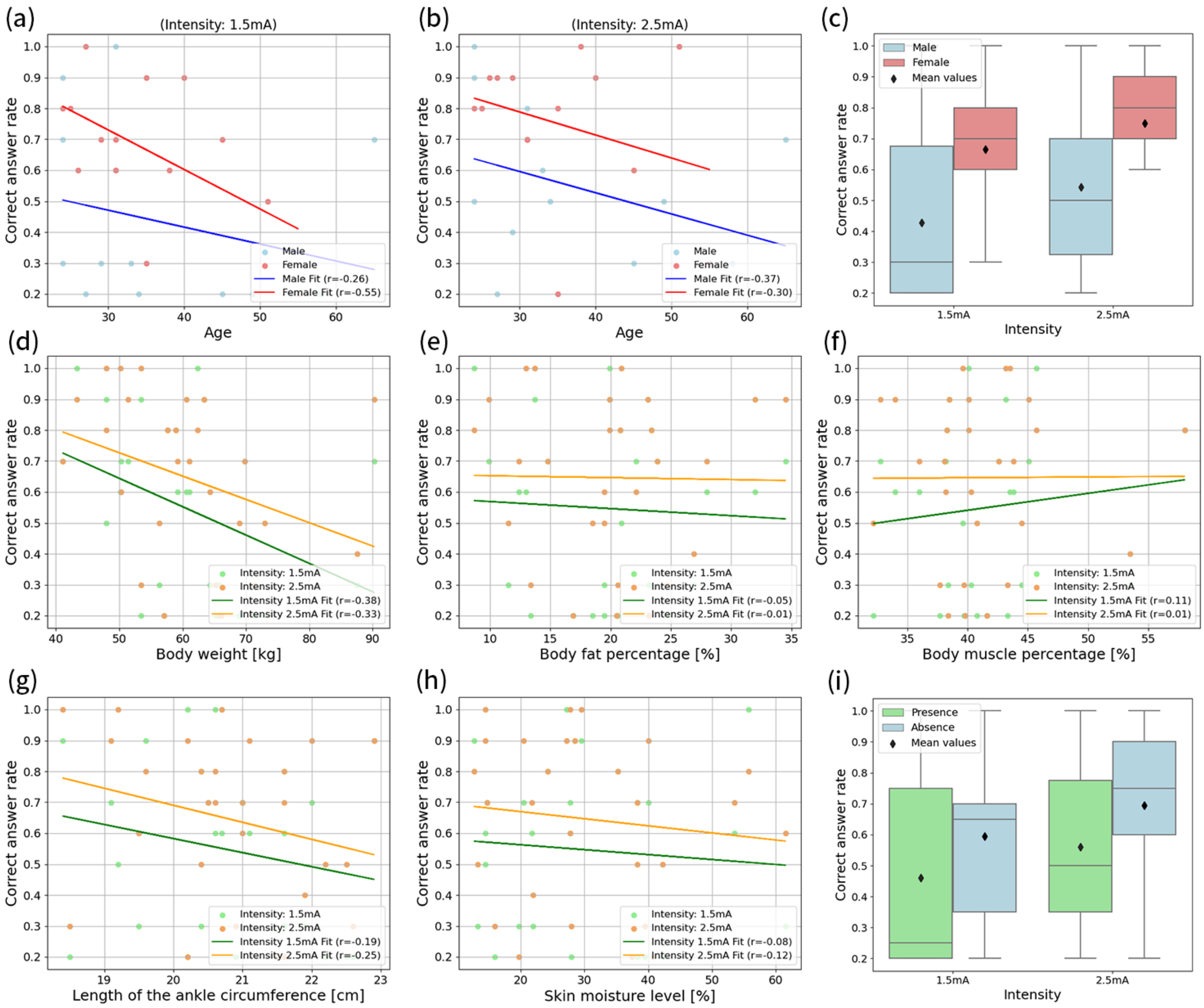

Figure 4: *The correct answer rate of the body tilt sensation for each demographic or biostructure metrics: (a, b) Relationship between the correct answer rate and the age at 1.5 mA or 2.5 mA of stimulation intensities. (c) Comparison of the correct answer rate by gender. (d, e, f, g, h) Relationship between the correct answer rate and body weight, body fat percentage, body muscle percentage, length of the ankle circumference, or skin moisture level. (i) Comparison of the correct answer rate by presence or absence of ankle hair.*

ure 4 (c) compares the correct answer rate by gender. A Student's t-test revealed significant differences between each gender for both 1.5 mA stimulation intensity ($p = 0.023$, $t = -2.41$) and 2.5 mA stimulation intensity ($p = 0.036$, $t = -2.22$). Figures 4 (d), (e), (f), (g), and (h) illustrate the correlations between the correct answer rate and various parameters, such as body weight, body fat percentage, muscle mass percentage, ankle circumference length, and skin moisture content, respectively. However, no sufficient correlation was observed. Figure 4 (i) compares the correct answer rate by the presence or absence of hair. A Student's t-test revealed no significant differences either in the 1.5 mA stimulation intensity ($p = 0.232$, $t = -1.22$) or 2.5 mA stimulation intensity ($p = 0.203$, $t = -1.31$).

Subsequently, we conducted a principal component analysis to examine the relationships among variables and the correlation between the principal components and the effects of ankle TES. We performed a Factor Analysis of Mixed Data (FAMD), which enables the analysis of both categorical and numerical data. The number of principal components was set at two, and the principal components were identified from body weight, body fat percentage, body muscle percentage, length of the ankle circumference, skin moisture level, and presence of ankle hair. Table 2 shows the principal component loadings. Component 1 is inferred to be a principal component associated with body size, given its high loadings for body weight, body fat percentage, and length of the ankle circumference. Component 2 is inferred to be a principal component

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Table 2: *Principal component loadings*

Variable	Component 1	Component 2
Body weight	0.734	0.079
Body fat percentage	0.549	0.320
Body muscle percentage	0.187	0.253
Length of the ankle circumference	0.604	0.067
Skin moisture level	0.089	0.536
Presence of ankle hair	0.004	0.540

associated with skin condition, given its high loadings of skin moisture level and presence of ankle hair. The explained variance ratios were 39.42% for Component 1 and 28.44% for Component 2. The cumulative explained variance ratio of the two principal components was 67.86%. Like the other biostructure metrics, the correlations between the correct answer rate and Component 1 or 2 were also investigated. However, no correlation was observed between Component 1 and the correct answer rate (at 1.5 mA stimulation intensity: $r = -0.26$, at 2.5 mA: $r = -0.24$), nor between Component 2 and correct answer rate (at 1.5 mA: $r = 0.17$, at 2.5 mA: $r = 0.12$).

Figure 5 illustrates the magnitude of the body tilt sensation for each demographic or biostructure metric. We have confirmed that the FS, BS, LS, and RS conditions induce the backward, forward, rightward, and leftward body tilt sensations, respectively (Fig. 3). Based on this, the magnitude of the body tilt sensation was calculated as follows: (1) Data for the NONE and SHAM conditions were excluded. (2) For the trials under FS, BS, LS, and RS conditions, the following values were calculated: the evaluation value of Q2, eight minus the evaluation value of Q2, the evaluation value of Q1, and eight minus the evaluation value of Q1, respectively. This is because higher values for Q1 (or Q2) indicate a stronger rightward (or backward) subjective body tilt sensation, while lower values indicate a stronger leftward (or forward) subjective body tilt sensation. (3) The average of all the values obtained in (2) was used as the evaluation value of the magnitude of the body tilt sensation. This value is interpreted as representing the magnitude of the body tilt sensation in the correct direction. Figure 5 (a) illustrates the correlation between the magnitude of the body tilt sensation and age at 1.5 mA of stimulation intensity. It indicates a correlation for the female data ($r = -0.57$). Figure 5 (b) illustrates the correlation between the magnitude of the body tilt sensation and age at 2.5 mA of stimulation intensity. It indicates no correlation for both male and female data. Figure 5 (c) compares the magnitude of the body tilt sensation by gender. A Student's t-test revealed no significant differences between each gender at the 1.5 mA stimulation intensity ($p = 0.147$, $t = -1.49$) and a significant difference at the 2.5 mA stimulation intensity ($p = 0.011$, $t = -2.73$). Figures 5 (d), (e), (f), (g), and (h) illustrate the correlations between the magnitude of the body tilt sensation and body weight, body fat percentage, body muscle percentage, length of the ankle circumference, or skin moisture level, respectively. However, no sufficient correlation was observed. Figure 5 (i) compares the magnitude of body tilt sensation by presence or absence of the ankle hair. A Student's t-test revealed no significant differences either in the 1.5 mA stimulation intensity ($p = 0.253$, $t = -1.17$) or in the 2.5 mA stimulation intensity ($p = 0.131$, $t = -1.56$).

Subsequently, we investigated the correlations between principal components obtained by FAMD and the magnitude of the body tilt sensation. However, no correlation was observed between Component 1 and the magnitude of the body tilt sensation (at 1.5 mA stimulation intensity: $r = -0.20$, at 2.5 mA: $r = -0.24$), nor between Component 2 and the magnitude of the body tilt sensation (at 1.5 mA: $r = -0.11$, at 2.5 mA: $r = -0.32$).

3. Discussion

Analysis of the relationship between the correct answer rate and demographic metrics revealed a negative correlation between age and the correct answer rate for females at a stimulation intensity of 1.5 mA (Fig. 4 a). This result indicates that the correct answer rate of female users decreases with increasing age at a stimulation intensity of 1.5 mA. Furthermore, there were significant differences between males and females in the correct answer rate of the body tilt sensation induced by ankle TES at both stimulation intensities of 1.5 mA and 2.5 mA (Fig. 4 c). This result indicates that females are more susceptible to the body tilt sensation induced by ankle TES than males. In addition, analysis of the relationship between the magnitude of the body tilt sensation and age revealed a negative correlation between age and the magnitude of body tilt sensation for the female data at a stimulus intensity of 1.5 m (Fig. 5 a). This result indicates that the magnitude of body tilt sensation of female users decreases with increasing age at a stimulation intensity of 1.5 mA. Furthermore, there was a significant difference between males and females in the magnitude of the body tilt sensation induced by ankle TES at a stimulation intensity of 2.5 mA (Fig. 5 c). These results support H1. Given the findings that suggest differences in the effects of ankle TES based on age and gender, it would be beneficial to report the age and gender of experimental participants in studies on ankle TES or TENS of the lower limbs.

At the relatively low stimulation intensity level of 1.5 mA, a negative correlation was observed between age and evaluation of ankle TES (the correct answer rate and magnitude of body tilt sensations) for female participants. Essentially, it suggests that aging makes it more difficult to induce the body tilt sensation at lower current intensities. This may be due to the increasing perception thresholds of receptors with age. A previous fundamental study reported that the density of mechanoreceptors in the skin decreases with age [TM16]. Furthermore, the perception threshold for tactile sensation increases with age, reducing the tactile shape discrimination ability in older adults [NAH*16]. In light of these reports, the perception thresholds of the receptors involved in the force sensation caused by ankle TES may change with age, resulting in age differences in the generation of body tilt sensations at the relatively low current intensity.

The above results suggest that male and older users are less likely to experience body tilt sensations at the stimulation intensity of at least 1.5 mA and 2.5 mA. As previously mentioned, since this study aimed to investigate the effects of fixed current values, we

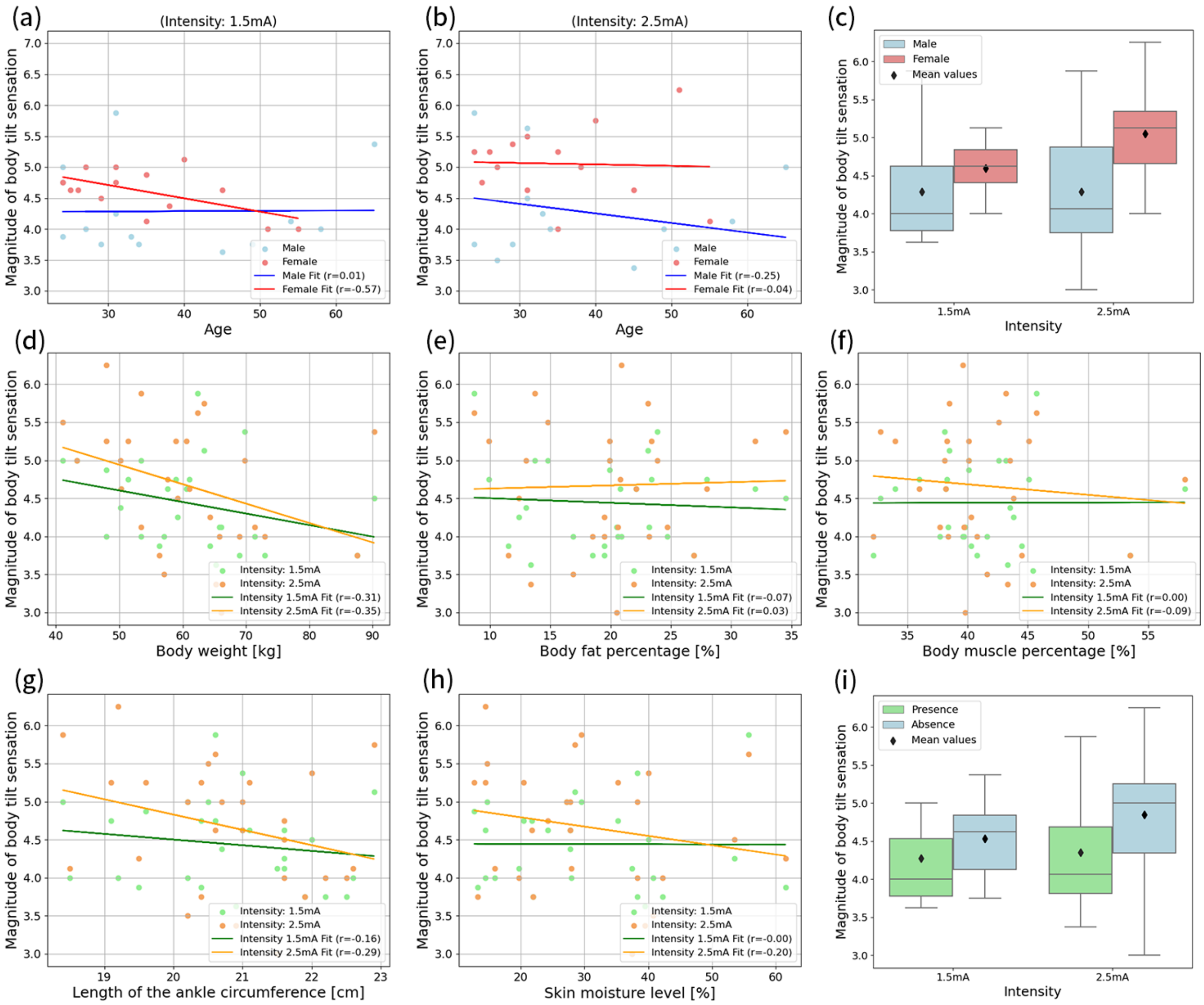

Figure 5: *The correct answer rate of the body tilt sensation for each demographic or biostructure metrics: (a, b) Relationship between the correct answer rate and the age at 1.5 mA or 2.5 mA of stimulation intensities. (c) Comparison of the correct answer rate by gender. (d, e, f, g, h) Relationship between the correct answer rate and body weight, body fat percentage, body muscle percentage, length of the ankle circumference, or skin moisture level. (i) Comparison of the correct answer rate by presence or absence of ankle hair.*

adopted the current values that do not exceed the minimum average value of the adjusted current value in the previous study on ankle TES [OMA*24] to meet the safety assurance. Therefore, a slightly higher current value may present the body tilt sensation in older male participants. However, if the threshold of the current at which males experience tingling pain is the same as or lower than that of females, then older males, who had difficulty in eliciting the body tilt sensation in this experiment, would have a very narrow range of current at which the body tilt sensation could be presented without discomfort. In such cases, ankle TES may not be a suitable sensory presentation technique for older males. The threshold for strong discomfort was not investigated in this study, and further research is required in this area.

We investigated the differences in the effects of ankle TES based on biological structure metrics such as body weight, body fat percentage, body muscle percentage, length of the ankle circumference, skin moisture level, and presence of ankle hair. However, none of these metrics showed a correlation with the correct answer rate or the magnitude of body tilt sensation (Fig. 4 d-i, Fig. 5 d-i). Furthermore, the two principal components derived from FAMD, Component 1 (representing body size) and Component 2 (representing skin condition), did not correlate with the correct answer rates or the magnitude of body tilt sensation. Thus, H2 was not supported. However, we should note that the interpretation of the results depends on the criteria used to define correlations. In this study, the analysis was conducted using the criterion of determin-

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ing that $|r| > 0.5$ is a sufficient correlation, but there is also a criterion of recognizing $|r| > 0.3$ as a moderate correlation [Coh88]. If this criterion is adopted, the relationship between body weight and the correct answer rate under both 1.5 mA and 2.5 mA of electrical stimulation intensity conditions, the relationship between body weight and the magnitude of body tilt sensation under both 1.5 mA and 2.5 mA stimulation intensity conditions, and the relationship between Component 2 and the magnitude of body inclination sensation under 2.5 mA stimulation intensity conditions are correlated. This means that body weight and Component 2 (representing skin condition) can also explain individual differences in sensation caused by ankle TES. This moderate correlation is rational, since the distance from the electrode to the target tendon varies with the user's body size, and the voltage across the electrodes of a constant-current circuit stimulator varies with skin conditions. In order to gather sufficient statistical evidence, a survey of a larger number of experimental participants should be conducted.

It is important to note that the results of this study indicated that there were differences in the effects of ankle TES based on gender and that the effects of ankle TES were correlated with age under certain stimulation intensity conditions, while no correlations were found with the biological structure metrics. However, it would be premature to conclude that biological structure can not explain individual differences in the effects of ankle TES. The first reason is that this study only examined a limited set of metrics. Therefore, other biostructure metrics not covered in this research may explain individual differences in the effects of ankle TES. The second reason is that demographic and biostructure metrics are confounding. For example, it is known that there are differences in pain receptors depending on gender differences [SLD*24]. Therefore, we should recognize that the results of this study only suggest that gender can better explain individual differences in ankle TES than the currently investigated biostructure metrics.

Based on the findings of this study, we discuss guidelines for future research involving ankle TES. First, we found that the effects of ankle TES vary by gender and age. Therefore, it would be desirable to report the gender and age of the experimental participants in the research involving ankle TES. Second, our findings suggest that ankle TES may be less effective in presenting sensations to specific demographic groups, such as older males. Consequently, alternative sensory presentation methods should be considered for applications targeting this group. For example, a haptic technique that presents force sensations by attaching vibrators against the ankles is proposed to reproduce the sensation of ground sway [NUMK24]. In applications that do not involve walking, it may be preferable to use such haptic techniques instead of ankle TES because it is acceptable for the vibrator to be pressed strongly against the ankles. Therefore, we propose guidelines suggesting that the age and gender of the target users should be considered when designing VR applications using haptic technology. However, although this study investigated individual differences in the effects of ankle TES, it did not examine individual differences in the effects of vibratory stimulation of the tendons. Therefore, in order to rigorously determine whether the above guidelines are applicable, individual differences in the effects of vibratory stimulation should also be investigated. If no individual differences are found, it would confirm that the above guidelines are applicable. Conversely, if individual differences in the effects of vibratory stimulation are observed, it would suggest that such differences arise from tendon stimulation in general, necessitating alternative guidelines such as personalized optimization.

4. Conclusion

In this study, in order to identify metrics related to individual differences in the effect of ankle TES, we investigated the relationships between the correct response rate or the magnitude of body tilt sensation by ankle TES and age, gender, or various biostructure metrics in 28 experimental participants.

The results showed a significant difference in the correct answer rate of the body tilt sensation based on gender. Furthermore, there was a negative correlation between age and the correct answer rate or the magnitude of body tilt sensation for female users at an electrical stimulation intensity of 1.5 mA. These results suggest that the age and gender of experimental participants should be reported in future studies on ankle TES or on TENS of the lower limbs and that analyzing the data separately for males and females may be beneficial to obtain detailed insights. Moreover, these results suggest that it may be challenging to induce body tilt sensation with ankle TES in some older males with stimulation intensities of 1.5 mA and 2.5 mA. On the other hand, none of the biostructure metrics examined in this study, including body weight, body fat percentage, body muscle percentage, length of the ankle circumference, skin moisture level, and the presence or absence of ankle hair, were correlated with either the correct answer rate or magnitude of body tilt sensation.

These findings are expected to contribute to evaluating the applicability of ankle TES or TENS to the lower limbs and developing appropriate research protocols.

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