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Abstract

The purpose of this study was to clarify the functional role of the heel pressure information for perceiving a backward-leaning position through a decrease in sensory information using local cooling on the heel in healthy participants (*n* = 11). The position of the center of pressure in the anteroposterior direction (CoPy position) while standing was represented as the percentage distance (%FL) from the hindmost point of the heel (0%FL) in relation to the foot length. The most backward-leaning position was measured under cool-heel condition and normal-heel condition. The perceptibility of six reference positions (45%FL, 40%FL, 35%FL, 30%FL, 25%FL, and 20%FL) was evaluated with regard to the reproducibility of these positions under both heel conditions. The most backward-leaning position under cool-heel condition was located significantly further backward than that under normal-heel condition. The absolute error at 25%FL under cool-heel condition was significantly larger than that under normal-heel condition. The sensory information from the heels may have a decisive meaning in the perception of the most backward-leaning position. At 25%FL, there may be no other sources of sensory information for sensory reweighting aside from the heel pressure for position perception under cooled condition.

Keywords: Heel pressure information; Cooling; Perception; Backward leaning; Sensory weighting

1. Introduction

The maintenance of human postural control in an upright position involves a complex process utilizing sensory information from visual, vestibular and proprioceptive receptors and cutaneous mechanoreceptors located on the soles of the feet [18,20]. The central nervous system (CNS) processes this sensory information to estimate the position [18]. The proprioceptive sensory information associated with postural control is processed through two routes in the CNS: cognitive processing, which acts on the perception of the body position, and sensorimotor processing, which regulates the posture via reflex and automatic loops [22].

Many researchers have reported on the perception of limb position, with perceptibility evaluated based on the reproducibility of a target limb position. Therefore, the perceptibility of the standing body position can be defined by the ability to reproduce a target standing position [7,8,10]. The standing position can be expressed based on the position of the center of pressure (CoP) projected on the base of support, and then the sway of the entire body is captured by the trajectory of the CoP using a force plate. The perceptibility of the standing position in the anteroposterior direction varies according to the standing position [7,8,10]. A standing position located near the quiet standing (QS) position shows a low perceptibility, while a position located far from the QS position shows a high perceptibility [7,8,10]. The body sway is observed no matter where the standing posture is maintained. When the subject maintains a standing position at an arbitrary position in the anteroposterior direction, a longer trajectory of sway indicates less stability, and a shorter trajectory indicates greater stability. In general, when the standing position is maintained in positions near the QS position, the body sway speed (trajectory length per unit time) is relatively low (high stability). In contrast, when in positions far from the QS position, the body sway speed is relatively high (low stability). In positions far from the QS position (low stability position), the posture control based on the postural perception for increasing stability according to the standing position is performed using cognitive processing [22] to avoid falling. In other words, the perceptibility of the standing position in the anteroposterior direction is related to the stability of the standing posture [10].

In standing positions far from the QS position with low stability and high perceptibility, there is a large change in the somatosensory information generated by the changes in the pressure on the sole and from the activation of muscles of the lower extremities [1]. Those large changes in somatosensory information are perceived with high accuracy, suggesting that they may contribute to positional information [1]. The position of the center of pressure in the anteroposterior direction (CoPy position) while standing is represented as the percentage distance (%FL) from the hindmost point of the heel (0%FL) in relation to the foot length. A large increase in muscle activity is typically observed twice: at about 30%FL and at 25%FL while gradually leaning backward from the QS position [1]. The standing position at about 30%FL is at the back end of the high-stability area, but the perceptibility of this standing position is not very high [10]. In contrast, the standing position near 25%FL is a position where the risk of falling is increased due to being near the most backward-leaning position, and the position perceptibility is extremely high [10]. In this standing position, the muscle activity of the rectus femoris and the tibialis anterior is significantly increased [1], and a large change is reported in the center-of-heel pressure due to a large change in the heel pressure distribution [9]. The large change in the center-of-heel pressure at about 25%FL was accurately perceived [9].

The functional role of the plantar pressure information in the standing posture maintenance has been reported in several articles. The methods of controlling the sensory information from the soles used in these reports can be divided into two types: increased sensory information by adding vibration stimulation to the soles [9,13,14,16], and decreased sensory information by anesthetizing the soles via cooling [1,2,3,17]. Kavounoudias et al. suggested that the pressure information from the heel plays a functional role as position information concerning the backward-leaning posture, since the body leaned forward from the QS position when the vibration stimulation was applied to the heel [13].

As previously described, a large change in the center-of-heel pressure is observed at about 25%FL, and the perception of this large change is good. This large change in the center-of-heel pressure is closely related to the shape of the calcaneus [9]. The large changes in sensory information due to a large change in the center-of-heel pressure is likely to be perceived near the most backward-leaning position and the position where the risk of backward falling is thus increased.

The present study therefore assessed the functional role of the large change in heel pressure information at about 25%FL to perceive a backward-leaning position through a reduction in sensory information using local cooling of the heel in healthy participants. Therefore, we investigated the effect of cooling the heel on the perceptibility of each backward leaning position, especially the 25%FL position. We hypothesized that since the perception of a large change in the heel pressure distribution at about 25%FL is good, this large change plays an important role as positional information when a backward-leaning position is achieved because this position is almost constant for each individual. Our working hypotheses were that the perceptibility of a standing position at about 25%FL would be specifically reduced by cooling the heel, and the most backward-leaning position would be significantly displaced backward compared with the normal-heel (non-cooled) condition.

2. Methods

2.1. Subjects

Eleven male university students without neurological or orthopedic impairment were selected among third- and fourth-year physical therapy students after obtaining their informed consent. Their mean (± standard deviation [SD]) age, height, weight, foot length and QS position were 22.5 ± 1.6 years old, 172.9 ± 7.1 cm, 63.2 ± 5.5 kg, 25.2 ± 0.8 cm and 44.8 ± 5.5%FL, respectively. All participants gave their informed consent to participate in this experiment, the protocol of which was approved by the institutional ethics committee of Kanazawa University in accordance with the Declaration of Helsinki (No. 162).

2.2. Apparatus

A force platform (WA1001; WAMI, Tokyo, Japan) was used to determine CoPy positions while subjects were standing with eyes closed. The electrical signals from the force platform were recorded on a computer (Inspiron 1300; Dell, Kawasaki, Japan) using the Vital Recorder software program (Kissei Comtec, Matsumoto, Japan) via an A/D converter (ADA16-32/2(CB)F; Comtec, Osaka, Japan) with a 1000-Hz sampling rate and 16-bit resolution. In addition, the electrical CoPy signal was sent to a computer (PC-9801RX2; NEC, Tokyo, Japan) via an A/D converter (PIO-9045; I/O DATA, Kanazawa, Japan) with 12-bit resolution to analyze the mean standing position for 3 seconds with a 50-Hz sampling rate. In measuring the perceptibility of standing position, an electronic buzzer connected to the force plate amplifier was used to sound a cue and inform the participants that each reference position was a position they needed to maintain for three seconds and memorize. When the participant had adjusted the CoPy position to within a range of 1.0 cm from the reference position, the buzzer sounded. A cooling device (Hiruta-ME HN-899) was used to decrease the sensitivity of the heel; this device was placed on the force platform (Figure 1). The device consisted of an aluminum-cooling plate under both heels. Four electronic cooling units (Peltiel devices) were placed under and in contact with the bottom side of the cooling plate.

2.3. Procedure

All measurements were performed with the participants standing barefoot and isolated, with both feet 5 cm apart. Before each task, the participants were instructed and practiced at least 10 times the following method for leaning their whole body: leaning actively and slowly their body from their QS posture to the most backward-leaning position using the ankles as the pivotal axis (ankle strategy), and maintaining the geometrical interrelationship among the body segments that was presented during the QS position. The experimenter observed the aspect of leaning of the participants during each task performance.

The CoPy position in the most backward-leaning position was measured for three seconds for five trials. The perceptibility of six reference positions was then evaluated based on the reproducibility of these positions. These measurements were conducted under two conditions: cool-heel condition and normal-heel condition. The order of these conditions was decided randomly for each subject, and each condition assessment was performed on different days.

The reference positions were set as follows: 45%FL, 40%FL, 35%FL, 30%FL, 25%FL, and 20%FL positions (Figure 2). These six reference positions were randomly carried out in an experimental block repeated seven times with a seated rest of three minutes between each block. We adopted 3 seconds to perform the memorization and reproduction of each reference position in this study. For the time elapsed from initially memorized reference position to reproducing it was within 20 seconds, which was within the limits of short-term memory [23], and to be easy maintaining reference and reproduction position especially in 20%FL. In addition, there are previous studies where the participants were instructed to hold the trunk for 3 seconds in the sagittal plane with eyes closed while standing [24], and to hold the elbow and the wrist joints for 3 seconds in sitting position [25]. Each reference position was reproduced according to the following procedure with reference to previous studies (Figure 3) [7,10]:

1) Participants maintained the QS posture for three seconds.
2) They voluntarily and slowly (within 10 seconds) moved their standing position by leaning backward until the buzzer sounded (the reference position) with the ankles as pivotal axes and then maintained and perceived the position for 3 seconds.
3) They sat on a chair behind the force platform for three seconds without returning to the QS position.
4) They then stood up, maintained the QS posture for three seconds, and reproduced the reference position.
5) They pressed the switch when they judged themselves to be standing in the reference position and maintained this position for three seconds.

For the cool-heel condition, the method of cooling the heel was conducted described as below. The heel was defined as the length from the hindmost point of the heel (0%FL) to 30% in relation to the foot length. Both heels of participants were placed on the cooling device in the sitting position, and the temperature of the cooling plate was cooled from room temperature to 1 °C. To verify the anesthetic effect of the cooling proceeding, the temperature of the cooling plate was kept at 1 °C, and the 2-point discrimination of the heel was measured every 10 minutes to establish whether or not the participant could perceive 1.3 times the value of the 2-point threshold before heel cooling in the longitudinal direction [21]. When the perceptibility exceeded 1.3 times the 2-point threshold before cooling, the experiment was started, and cooling was sustained during the experiment.

2.4. Data analyses

For each participant, we calculated the mean CoPy positions for 3 seconds while maintaining the following postures: the most backward-leaning position, leaning during perceiving, and reproducing each reference position. The perceptibility was evaluated based on the reproducibility of the reference position. The reproducibility was measured by the absolute error calculated using the formula below. A smaller absolute error means higher perceptibility.

$$\text{Absolute error} = |(\text{reproduced position}) - (\text{reference position})|$$

2.5. Statistical analyses

The Shapiro-Wilk test was used to confirm the normal distribution of all data. A one-way repeated-measures analysis of variance (ANOVA) was used to study the effect of the reference position on the absolute error under the normal-heel condition to confirm the reproducibility of this evaluating method by comparing previous reports. A post-hoc multiple comparison analysis using Tukey's honestly significant difference test was used to assess the significance of differences found by the ANOVA. A paired t-test was used to assess the significance of differences in the absolute error between both conditions at each reference position and at the most backward-leaning position. All statistical analyses were performed using the SPSS 14.0J software program (SPSS Japan, Tokyo, Japan).

3. Results

3.1. The effect of the reference position on the absolute error under normal-heel condition

The absolute errors in each reference position under the normal-heel condition are shown in Figure 4. The absolute error decreased as the leaning position shifted further backward. A significant effect of the reference position was found on the absolute error ($F(5,60)=11.15$, $p<0.01$) (Fig. 4). After multiple comparisons, the absolute error at 20%FL and 25%FL were shown to be significantly smaller than those at 35%FL, 40%FL, and 45%FL (Fig. 4).

3.2. The most backward-leaning position

The most backward-leaning position under normal-heel condition was 20.0%±1.7%FL, and that under cool-heel condition was 18.8%±0.8%FL. The most backward-leaning position under cool-heel condition was located significantly further backward than that under normal-heel condition ($t=2.89$, $p<0.05$).

3.3. Perceptibility of each reference position

The absolute error in each reference position under both conditions are shown in Figure 5. The absolute error in 20%FL under normal-heel condition was 2.0%±0.9%FL, and that under cool-heel condition was 1.9%±0.6%FL, there was no significant difference between both conditions ($t=-0.30$, $p>0.05$) (Figure 5A). The absolute error in 25%FL under cool-heel condition (2.8%±1.0%FL) was significantly larger than that under normal-heel condition (2.1%±0.8%FL) ($t=2.78$, $p<0.05$) (Figure 5B). The absolute error in 30%FL under normal-heel condition was 3.8%±1.2%FL, and that under cool-heel condition was 3.5%±1.0%FL, there was no significant difference between both conditions ($t=-0.71$, $p>0.05$) (Figure 5C). The absolute error in 35%FL under normal-heel condition was 4.5%±1.2%FL, and that under cool-heel condition was 4.1%±1.5%FL, there was no significant difference between both conditions (t=-0.72, p>0.05) (Figure 5D). The absolute error in 40%FL under normal-heel condition was 4.5%±1.6%FL, and that under cool-heel condition was 5.3%±3.0%FL, there was no significant difference between both conditions (t=1.34, p>0.05) (Figure 5E). The absolute error in 45%FL under normal-heel condition was 5.6%±2.3%FL, and that under cool-heel condition was 5.6%±3.5%FL, there was no significant difference between both conditions (t=0.07, p>0.05) (Figure 5F).

4. Discussion

4.1. The effect of the reference position on the absolute error under normal-heel condition

An effect of the reference position on the absolute error under normal-heel condition was detected. This finding was similar to that of previous reports, which used the same method as the present study to evaluate the perceptibility of the standing position [7,10], thus confirming the reproducibility of this method. In addition, the absolute errors in each reference position under normal-heel condition were similar to the values in those previous reports indicating average responses of the subjects in this study [7,10].

4.2. The most backward-leaning position

The most backward-leaning position under cool-heel condition was located significantly more backward than that under normal-heel condition. Furthermore, even if the most backward-leaning position was displaced even further backward, under cool-heel condition, all participants were able to return their body forward from that position without falling. Previous study reported that the self-reported most backward-leaning position was near 19%FL, the participants could return forwardly after maintaining this position [7]. Thus, the most backward-leaning positions under both conditions were not the position at which humans actually start falling backward. Instead, the most backward-leaning position in this study could be considered the self-reported rearmost standing position at which the body can still be returned forward to avoid falling backward. Therefore, the starting position of backward falling while standing in a leaning position may actually be slightly further back than the most backward-leaning position. The most backward-leaning position may maintain a certain degree of leeway with respect to the position at which one starts falling backward and may be perceived as the most-backward position where it is still possible to return the body forward without losing balance. The backward displacement of the most backward-leaning position under cool-heel condition means that the margin for ensuring safety decreases, and consequently, the risk for backward falling is increased compared with normal-heel condition.

Based on the present findings, the pressure sensation from the heel may be highly weighted in the sensory reference frame [11,16,26] to perceive the most backward-leaning position. The compensation effect (reference) by other sensory channels was not found to be sufficient to maintain the original most backward-leaning position. Thus, the sensory information from the heels may play a decisive role in the perception of the most backward-leaning position.

4.3. The perceptibility of the standing position

Interestingly, the absolute error at 25%FL under normal-heel condition was similar to that at 20%FL under the same condition. These results clearly demonstrate that the positional perceptibility at this position was markedly high. Near 25%FL, the heel pressure distribution was shown to be changed largely based on the shape of the calcaneus, and this large change was correctly perceived [9]. Therefore, the standing position at 25%FL can be considered to be correctly perceived based on this large change in the heel pressure distribution. Given the high perceptibility at 25%FL and 20%FL, we conclude that, in positions close to the most backward-leaning standing position, there are at least two stages of safety systems in place in order to perceive the position and prevent the body from reaching the falling start position.

It has been shown that the role of vestibular information for body position perception has limitation [4,6]. Moreover, it has been reported that the information from the otolith organs does not work well if the body inclination is less than 7 degrees [4,5,6]. The body inclination angle when leaning backward from the QS position to 25%FL was calculated based on the mean height, mean QS position, and mean foot length of the subjects. The mean height of the center of gravity of the whole body calculated from mean height was 96.8 cm considering that the relative height of the center of gravity to the body height is 56%. Because the mean foot length is 25.2cm, the movement range of 30%FL from 55%FL to 25%FL is 7.6 cm. The body inclination angle when leaning backwardly the range of 30%FL calculated from these values is about 4.5 degrees, which was less than 7 degrees described above. Therefore, we can also conclude that the involvement of vestibular information for the standing position perception was small in this study.

A significant effect of heel cooling was only observed for the perceptibility of the standing position at 25%FL. It was revealed that the sensory information generated from the large change in heel pressure distribution at 25%FL is highly weighted in the reference frame to perceive the standing position, proving the importance of the value at that position. In the control of bipedal human posture, the most reliable inputs are emphasized, i.e. upweighted by the CNS, while less reliable sensory inputs are deemphasized, i.e. downweighted [12]. Nashner and Berthoz reported that the relative contribution of each sensory system changes depending on environmental conditions, a phenomenon referred to as “sensory reweighting” [19]. Therefore, because of the reduced reliability of the sensory information due to the large change in the heel pressure distribution under cool-heel condition, it is conceivable for the body to increase the weighting of sensory information from other sources. However, at 25%FL, the position perceptibility was significantly lower under cool-heel condition than that under normal-heel condition. Therefore, when the sensory information associated with a large change in heel pressure distribution decreased, there may not have been any other sensory information sources whose weighting could be increased (“sensory reweighting”). At reference positions other than 25% FL, there was no significant effect of heel cooling on the perception. At these reference positions (other than 25%), it is conceivable that the weighting of the heel pressure information during cooling was reduced, while other sources of sensory information were successfully reweighted.

In previous studies about the perception of limb position, the perceptibility has been evaluated by the reproducibility of joint position. Some of them have compared the reference position moved manually by the experimenter from the starting position and reproduced position attempted by the participant. Then, the reference position was set passively. Conversely, the reproduction position was set actively. The difference of these movement methods seemed to lead different sensory information [7]. For this reason, the reference position setting and the reproduction of the reference position were performed actively. In addition, in this study, the participants had to get the sitting position just after the setting of reference position instead of getting back to the starting position. The reason of sitting was to avoid the sensory information that can be used as a clue, when the participant moves back directly to the starting position from the reference position and consequently improve the measurement accuracy. Although the heel cooling affected the perception in 25%FL, what can explain the important of the sensory information from the heel at this position, other positions were not affected by the heel cooling. The limitation of this study is that we could not identify the sensory information used as clue for postural perception in position other than 25%FL.

In the present study, only the heel was cooled to clarify the functional role of the pressure sensation from the heel in the perceptibility of the standing position while leaning backward. The weight load on the sole in the standing position is also distributed to the forefoot and toes, not only the heel. Although the plantar pressure distribution under the standing position differs greatly according to the standing position in the anteroposterior direction, the load on the forefoot does not become zero even in the backward-leaning position. Consequently, although the pressure sensation from the forefoot is considered to contribute to the perception of the backward-leaning standing position, the contribution of forefoot sensory information was not clarified in the present study.

The results of this study support the need of further researches on new methods to compensate the lack of sensory information during backward leaning in individuals with decreased foot sole sensibility in order to prevent backward falling. This study aimed to clarify the functional role of the heel pressure information for perceiving a backward-leaning position in eleven healthy participants. The most backward-leaning position under cool-heel condition was located significantly further backward than that under normal-heel condition. The sensory information from the heels may have a decisive meaning in the perception of the most backward-leaning position. The absolute error at 25%FL under cool-heel condition was significantly larger than that under normal-heel condition. At 25%FL, there may be no other sources of sensory information for sensory reweighting aside from the heel pressure for position perception under cooled condition.

Author statement

We guarantee the originality of the manuscript, we are responsible for the data and experimental results of the article.

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Declaration of Competing Interest

The authors declare that they have no financial conflict of interest.

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Figure legends

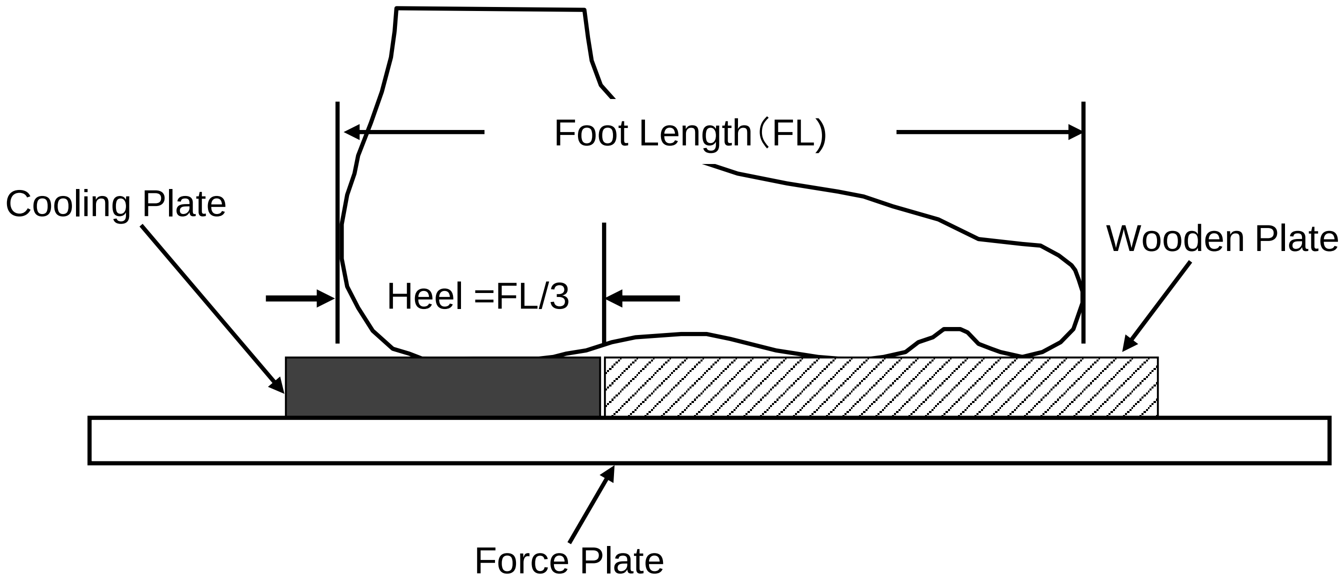
Figure 1. Schematic illustration of the experimental setup.

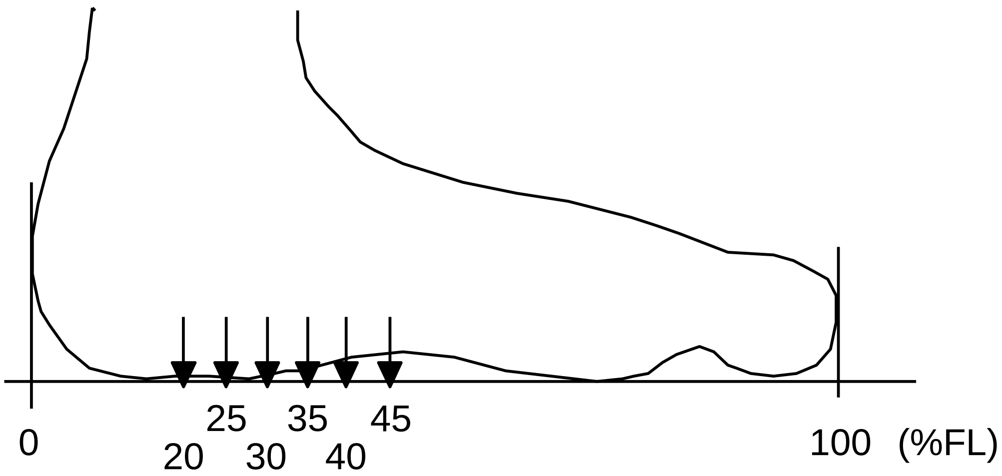
Figure 2. Reference positions.

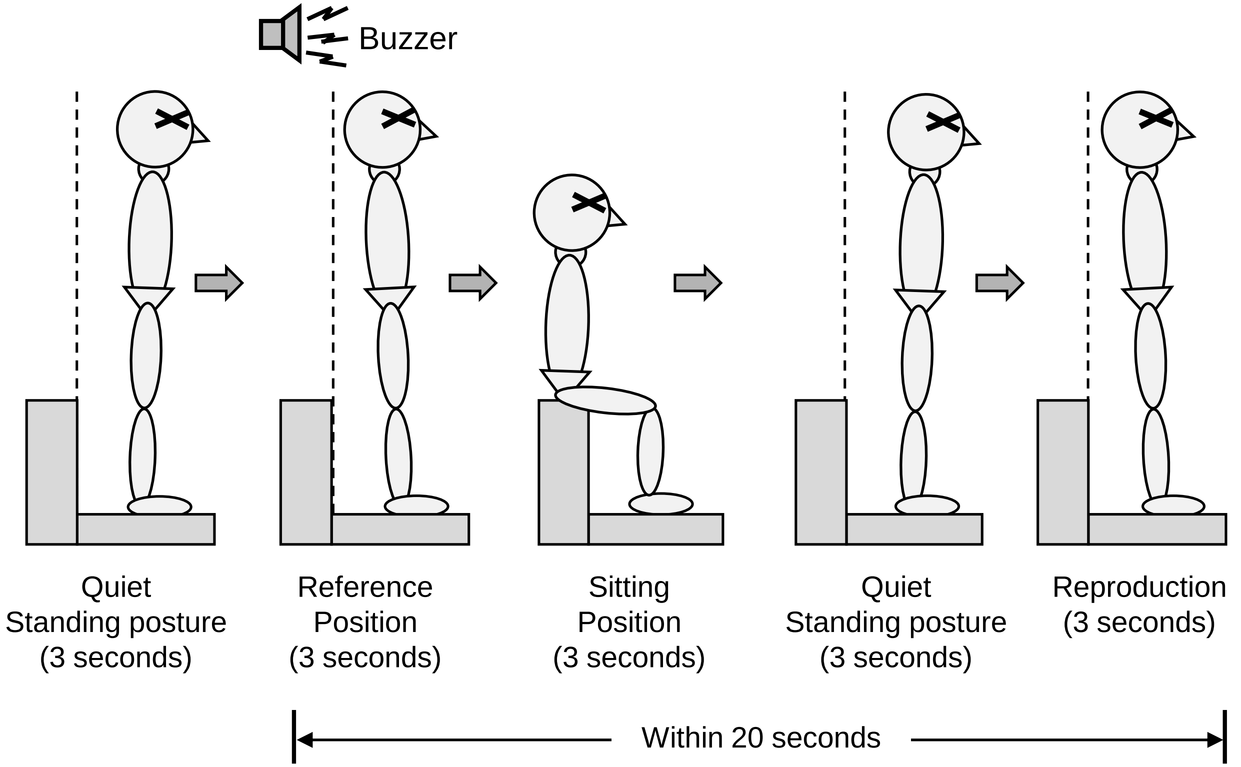
Figure 3. Experimental protocol for reproducing reference positions with eyes closed (Reproduced from Fujiwara et al. [7]).

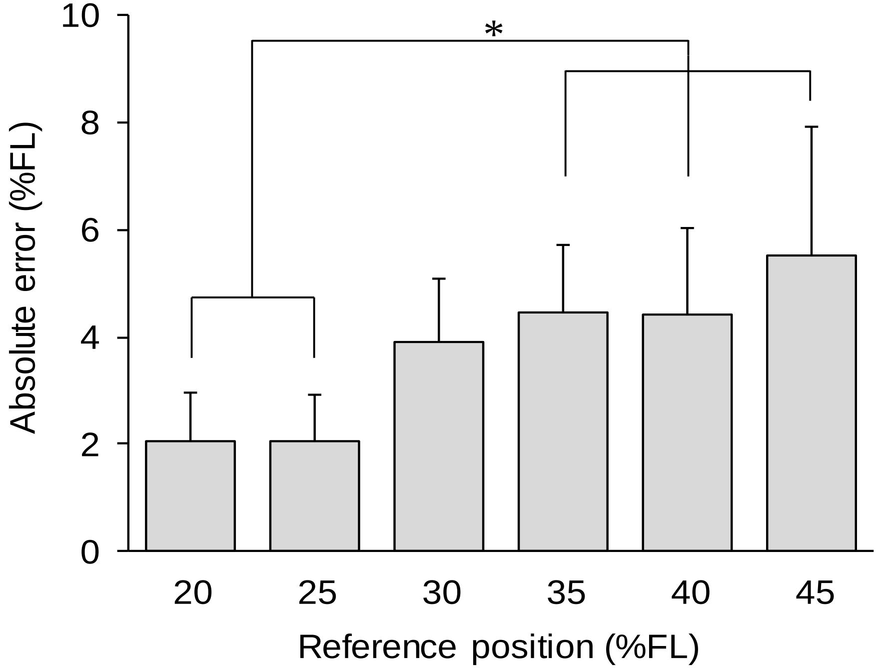
Figure 4. Mean values and standard deviations of the reproduction absolute error for each reference position under normal-heel condition. *: The absolute errors at 20%FL and 25%FL were significantly smaller than those at 35%FL, 40%FL, and 45%FL.

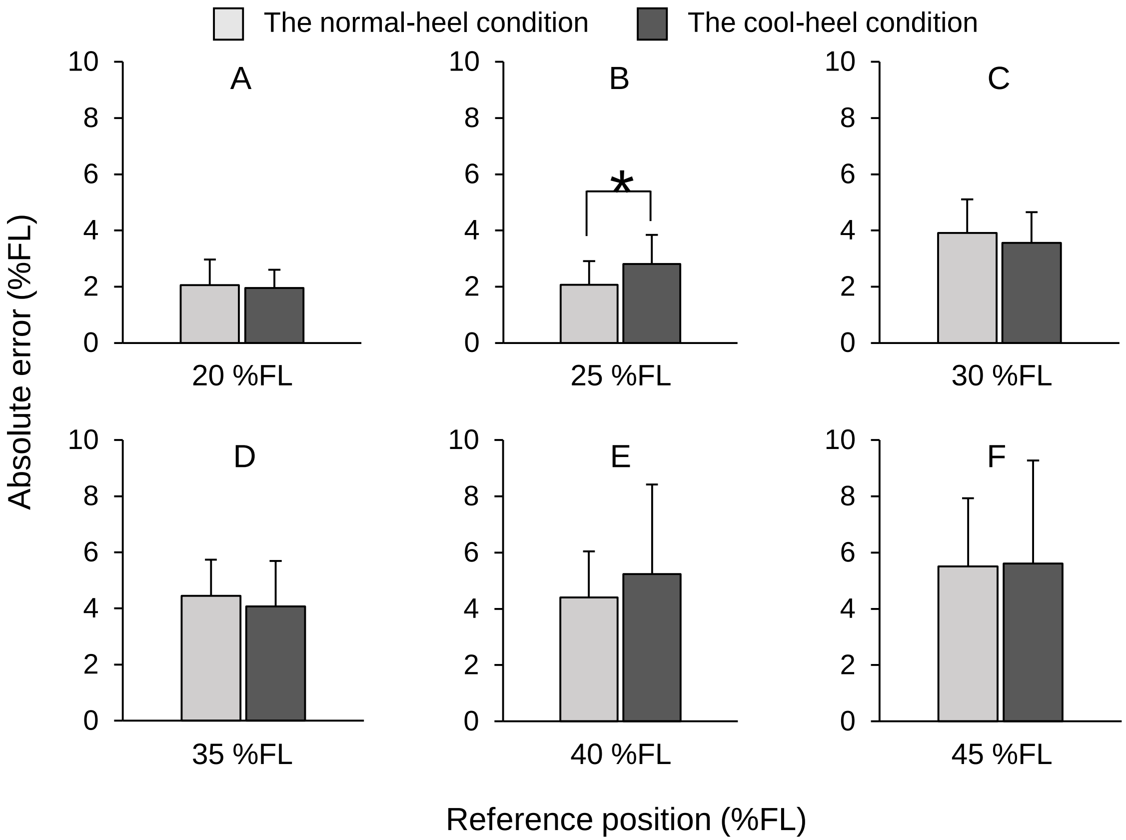
Figure 5. Means and standard deviations of the reproduction absolute error in each reference position under both conditions. A: 20%FL, B: 25%FL, C: 30%FL, D: 35%FL, E: 40%FL, F: 45%FL. *: There is a significant difference between both conditions ($p<0.05$).


Foot Length（FL)
Cooling Plate
Wooden Plate
Heel =FL/3
Force Plate


25
35
45
0
20
30
40
100
(%FL)


Buzzer
Quiet
Standing posture
(3 seconds)
Reference
Position
(3 seconds)
Sitting
Position
(3 seconds)
Quiet
Standing posture
(3 seconds)
Reproduction
(3 seconds)
Within 20 seconds


10
8
6
4
2
0
*
Absolute error (%FL)
20
25
30
35
40
45
Reference position (%FL)



The normal-heel condition
The cool-heel condition
Absolute error (%FL)
A
B
C
D
E
F
*
0
2
4
6
8
10
20 %FL
25 %FL
30 %FL
35 %FL
40 %FL
45 %FL
Reference position (%FL)