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Effect of Heel Pad Pressure on the Perception of Backward-Leaning Standing Positions

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Abstract

The purpose of this study was to investigate the effects of the additional heel pressure sensory information using a nut taped under the calcaneal tuberosity on the perceptibility of the backward leaning standing position. Fifteen young subjects participated in this experiment. The center of pressure in the anteroposterior direction position was represented as the percentage distance from the hindmost point of the heel in relation to the foot length (%FL). The perceptibility of 5 reference positions (40%FL, 35%FL, 30%FL, 25%FL, and 20%FL) was evaluated based on the reproducibility of these positions. The ratio of the absolute error under the normal heel condition to the absolute error under the heel pressure condition in each reference position was calculated as the pressure effect index. There was no main effect of condition on the absolute error. Three reference positions (40%FL, 30%FL, and 20%FL) showed significant negative correlation between the absolute error under the normal heel condition and the pressure effect index. Increasing the heel pressure sensation should be efficient to compensate for the lack of sensory information while leaning backwards in a standing position.

Keywords: Heel pad; Pressure; Backward-leaning; Position perception

Abbreviations: QS: Quiet Standing; CoPy: Center of Pressure in the Anteroposterior Direction: %FL: % Foot Length

Introduction

In standing posture control, it is important to perceive the relationship between the standing posture and the direction of gravitational force. When both arms are rapidly flexed to the front from the quiet standing (QS) posture, the postural muscles are activated 20 to 30 ms earlier than the focal muscles of the arms (the anterior deltoid) [1]. This anticipatory activation of the postural muscles during the QS position was significantly slower than that in the standing position near the most forward-leaning position and was significantly faster than that in the standing position near the most backward-leaning position [1]. Therefore, the preceding time of the postural muscle activation depends on the initial standing position just before the arm movement. In contrast, the pre-activation time of the postural muscles in an illusionary forward-leaning standing position induced by Achilles' tendon vibration associated with trunk fixation was not different from the self-reproduced perceived standing position, which was more forward-leaning than the position during the tendon vibration [2]. Taken together, these reports suggest that the initial standing position just before arm movement was accurately perceived, and the preceding time and/or the magnitude of activity of the postural muscles changes based on the postural perception.

The perceptibility of the standing position in the anteroposterior direction reportedly varies according to the standing position. The standing positions located far from the QS position showed low stability, and their perception was markedly higher than in positions near the QS position [3]. The present study is based on the findings from our previous study, which concluded that a large change in sensory information from the foot may provide important cues regarding the perception of standing positions with low stability [4]. Large changes in the somatosensory information generated from large changes in the pressure at the first metatarsal head, the pressure at the first toe and the activation of the toes' flexor muscles during forward leaning [4] as well as the pressure changes at the heel while leaning backwards [5] may contribute to the position information.

In their studies on the relationship between the sensory information from the sole and the standing position, Kavounoudias et al. reported that subjects leaned forward when vibration was applied to the heel in the standing position, whereas they leaned backward when vibration was applied to the forefoot [6,7]. It is believed that the body position is misinterpreted to be leaning backwards due to the vibration applied to the heel, thereby generating a reaction of leaning forward. In the same way, when a vibration is applied to the metatarsal region of the foot sole, there is an illusionary perception of the body leaning forward, which generates a reaction of leaning backwards. These findings therefore suggest that the sensory information from the foot sole contributes to the position information while maintaining a standing posture.

The aspects of illusory sensation induced by vibration on the same region can reportedly be perceived differently according to the subject [8]. Thus, the interpretation of the applied sensory information may differ among subjects. In other words, even if the same sensory information is applied, the effect on the postural control may be different, according to an individual's body condition and interpretation of the sensory information. There have also been studies with subjects whose standing stability is decreased, such as elderly people [9] and patients with Parkinson disease [10], wherein the stability was improved using a specially designed insole to increase sensory information from the sole. However, young people and healthy subjects failed to show similar effects of this sole on their standing stability [9,10]. These studies suggest that positive effects may be achieved by incorporating additional sensory information into the postural control in subjects with low standing stability. In contrast, however, the incorporation of such sensory information might have no effect on or even disturb the postural control in healthy subjects.

The muscular sensory information from the toe flexors and the pressure information from the toes play important roles in gathering forward-leaning positional information [4]. However, when leaning backwards, the calcaneus region mainly supports the body weight, generating important pressure information that may contribute to the backward-leaning positional information.

The purpose of this study was to investigate the effects of additional pressure sensory information from the heel on the perceptibility of the standing positions while leaning backwards. The hypothesis was as follows: A mechanical increase in the heel pressure information will improve the perceptibility of the standing position in subjects with low perceptibility.

Methods

Subjects

A total of 15 subjects (7 females and 8 males) without neurological or orthopedic impairments were randomly selected for this experiment. Their mean (± standard deviation [SD]) age, height, weight, and foot length were 20.9 ± 1.3 years, 163.8 ± 9.3 cm, 60.9 ± 10.2 kg, and 24.5 ± 2.0 cm, 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 (Approvement No. 367).

Apparatus

A force platform (WA1001; WAMI, Tokyo, Japan) composed of three load cells was used to measure the center of pressure in the anteroposterior direction (CoPy) position while participants were standing with eyes closed and bare feet. The electrical signals from the force platform were recorded on a computer (Inspiron 1300; Dell Japan, 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. To measure the perceptibility of the standing position, an electronic buzzer connected to the force plate amplifier was used to sound a cue and inform the participants when they had reached each reference position, at which point they held the position for 3 seconds and memorized it. When the participant had adjusted the CoPy position to within 1.0 cm of the reference position, the buzzer sounded.

Two types of nut made of stainless steel (large nut: diameter of 5 mm, thickness of 3 mm; small nut: diameter of 4 mm, thickness of 2 mm) were used to add pressure stimulation to the heel pad while standing. The nut size adopted for the experiment was selected according to each subject's preference after 5 minutes of standing on the nut, starting with the large nut. For subjects who reported any pain or discomfort when the large nut was placed under the heel pad, the small nut was selected after confirming no pain or discomfort. The nut was taped using double-faced tape under the calcaneal tuberosity, which was identified by palpation and ultrasound imaging.

Procedure

This experiment was conducted under two conditions: the heel pressure condition (standing on the nut) and the normal heel condition. The order of these conditions was decided randomly for each subject. The CoPy position was represented as the percentage distance (%FL) from the hindmost point (0%FL) of the heel in relation to the foot length. Participants were instructed to move the body with the ankle as the pivotal axis and to maintain the geometrical interrelationship among the body segments that was presented during the QS position. Under both conditions, this experiment was conducted by the procedure described below.

The CoPy position was measured first for three seconds in the QS posture for five trials. Next, the CoPy position during the most backward-leaning standing position was measured for three seconds for five trials. In these trials, the participants were instructed to actively and slowly lean the body from their QS posture to the most backward-leaning position. The perceptibility of five reference positions was then evaluated based on the reproducibility of these positions to investigate the effect of the increased heel pressure stimulation using the nut on the perception of the standing position. The reference positions were set as follows: 40%FL, 35%FL, 30%FL, 25%FL, and 20%FL position. An experimental block consisted of five random reference positions repeated seven times with a seated rest of three minutes between each blocks. Each reference position was reproduced according to previous study [3] (Figure 1) as follows: First, participants maintained the QS posture for three seconds (Figure 1a). Then, they voluntarily and slowly (within 10 seconds) leaned backward until the buzzer sounded (the reference position) with the ankles as the pivotal axes and maintained and perceived the position for 3 seconds (Figure 1b). They then sat on a chair behind the force platform for three seconds without being instructed to return to the QS posture (Figure 1c). They then stood up and maintained the QS posture for three seconds (Figure 1d). Finally, they reproduced the reference position and pressed the switch when they felt that they were standing in the reference position and maintained this position for three seconds (Figure 1e).

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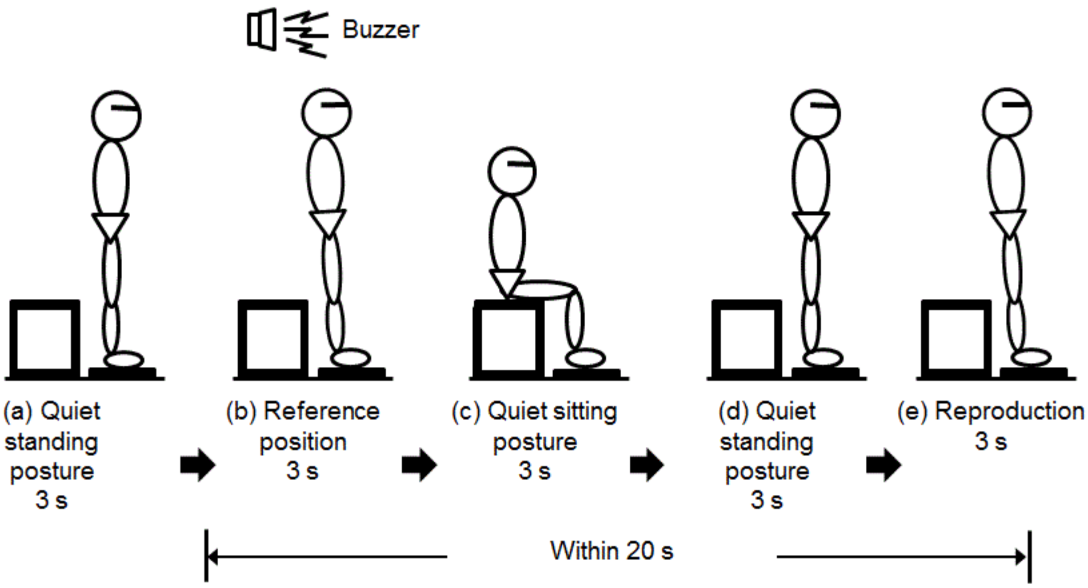

Figure 1: Experimental protocol for reproducing reference positions (Reproduced from Fujiwara, Asai et al.).

In each case, the time elapsed from initially memorizing the reference position to reproducing it was within 20 seconds, which was within the limits of short-term memory [11].

Data analyses

For each subject, we calculated the mean CoPy positions for three seconds while maintaining the QS and most-backward-leaning positions. For each position, the mean value of repeated measurements is reported as the subject's representative value.

The perceptibility was measured based on the reproducibility of the reference positions. The relationship between the reference position and perceptibility was investigated based on the reproduction absolute error. The reproduction absolute error (absolute error) was calculated using the following formula: Absolute error = |(reproduced position) – (reference position)|

The ratio of the absolute error under the normal heel condition to the absolute error under the heel pressure condition in each reference position was calculated as the pressure effect index. This value is 100% in cases where the absolute error under both conditions is the same and <100% in cases where the absolute error under the heel pressure condition is smaller than that under the normal heel condition.

Statistical analyses

The Mann-Whitney U test was used to study the effect of the nut size on all measurement values for nine subjects using a large nut and six subjects using a small nut. Because there were no significant differences in any values between the nut-size groups, the 15 subjects' data were used as a single group under the pressure condition for the tests described below. A paired t-test was used to assess significant differences under both conditions for the QS position and most-backward-leaning position.

A two-way repeated-measures analysis of variance (ANOVA) was used to study the effect of the reference position and condition on the absolute errors. In each reference position, Pearson's correlation coefficient was used to study the relationship between the absolute error under the normal heel condition and the pressure effect index. The alpha level was set at $p<0.05$. All statistical analyses were performed using the SPSS 14.0J software program (SPSS Japan, Tokyo, Japan).

Results

The QS position and the most-backward-leaning position

The average QS position was 41.6% ± 3.6%FL under the normal heel condition and 41.4% ± 4.9%FL under the heel pressure condition, showing no significant difference in the QS position between the conditions. The most-backward-leaning positions were 18.8% ± 1.2%FL under the normal heel condition and 18.9 ± 1.0%FL under the heel pressure condition, showing no significant difference in the most-backward-leaning position between the conditions.

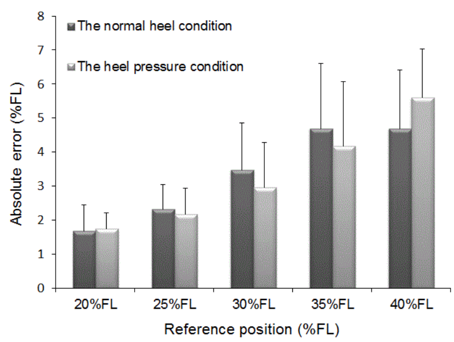

Figure 2: Means and standard deviations of reproduction absolute error in reference positions (%FL: % Foot Length).

The absolute error

The absolute errors in each position under both conditions are shown in Figure 2. There was no two-factor (reference positons and conditions) interaction in the absolute errors (F=2.17, p=0.127). There was no main effect of the condition on the absolute error (F(4,145)=0.08, p=0.787).

However, there was a main effect of the reference position on the absolute error (F(4,145)=37.4, p<0.01), as the absolute error decreased significantly from 40%FL to 20%FL.

The relationship between the absolute error under the normal heel condition and the pressure effect index

The relationship between the absolute error under the normal heel condition and the pressure effect index is shown in Figure 3. Each reference position showed a negative correlation, and 3 reference positions (40%FL, 30%FL, and 20%FL) showed a significant negative correlation (40%FL: r=-0.65, p<0.01; 30%FL: r=-0.63, p<0.05; and 20%FL: r=-0.69, p<0.01).

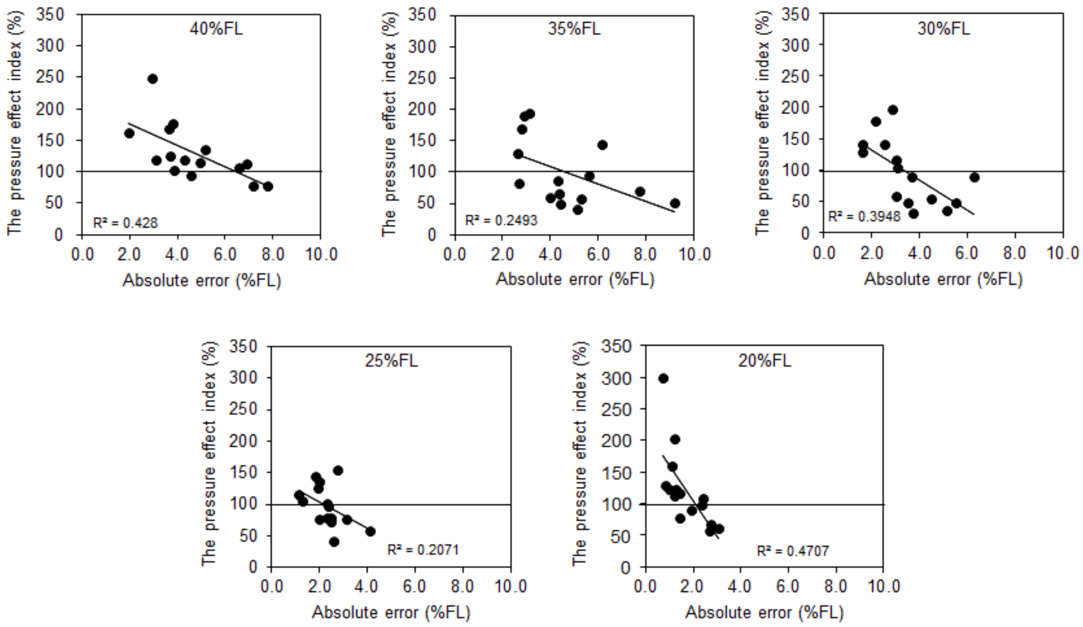

Figure 3: The relationship between the absolute error under the normal heel condition and the pressure effect index (%FL: % Foot Length).

Discussion

There is a consensus that the pressure sensation of the sole contributes to the perceptibility of the standing position and stability of the standing posture via the cooling of the sole [4,5,12], vibration [5-7], and anesthesia [13]. No effect of increased heel pressure information on the standing position was found at the QS or most-backward-leaning positions. If the increased heel pressure using a nut was a nociceptive stimulation, both the QS position and the most-backward-standing position would have deviated forward under the heel pressure condition and not the normal heel condition, in order to reduce the pressure at the heel. Therefore, the increased pressure stimulation to the heel was probably not producing any nociceptive stimulation. In addition, the results of this study were different from those in a previous report noting forward deviation of the standing position under increased pressure stimulation of the heel using vibration [5-7]. This suggests that the heel pressure stimulation in this study may not be strong enough to induce any deviation of the standing position.

The hypothesis posited in the present study was supported by the results: An effect of the increased heel pressure on the perceptibility of the standing position was detected even in healthy young subjects whose perceptibility of the backward-leaning position was low. However, this effect was not obvious at the reference positions of 35%FL and 25%FL. The reference position of 35%FL is the average position at which patellar movement is observed while leaning backwards from the QS position [14]. Large changes in the sensory information around the patella due to upward movement of the patella contribute position information while leaning backward [15]. The position of 25%FL was near the position at which the heel pressure distribution changes markedly while leaning backwards. Therefore, the large change in the sensory information accompanied by the change in the heel pressure distribution near 25%FL should be important information for the perception of the standing position [5].

Reference positions 35%FL and 25%FL were probably approximate positions at which a large change in the sensory information occurred. This may have overshadowed any effect of increased heel pressure information, as other sensory information was deemed more useful as clues regarding the position. However, these findings also suggested that the effect of the increased pressure information on the perceptibility was higher at 40%FL, 30%FL, and 20%FL in subjects with low perceptibility, as these were positions relatively far from the positions at which large changes in the sensory information occur.

This study was carried out in healthy young subjects. However, it has been reported that elderly subjects tend to show a reduced knee extension while standing compared with young subjects [16,17]. The patella is located closer to the femur during knee flexion in the standing position than during knee extension [18]. Therefore, the patella may not move while leaning backwards when there is slight knee flexion, which is relatively frequent in elderly individuals. In such cases, the change in the sensory information typically used as a clue to interpret the standing position may not occur, due to a lack of patellar movement. It was also reported that the two-point discrimination in elderly subjects is less sensitive than in younger subjects [19]. In addition, the senses of position and movement are also affected by age [20,21]. However, Qiu et al. reported that the standing stability of elderly subjects was improved by the addition of enhanced somatosensory information from the sole [9]. Given that the sensory information accompanied by movement of the patella and the sensibility of the sole seem insufficient in elderly individuals, increasing the heel pressure sensation should help compensate for the lack of sensory information when leaning backwards in a standing position.

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