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Original Article

Contribution of vision and tactile sensation on body sway during quiet stance

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Abstract. [Purpose] This study examines the contribution of vision and tactile sensation on body sway during quiet stance. [Participants and Methods] Sixteen healthy participants maintained quiet stance. The mean distance between the neutral center of pressure (COP) and that at the peak deviated position, indicating how quickly humans initiate the swaying of the body back to the neutral position, was calculated (COPpeak). [Results] The displacement of the COP in both the anterior–posterior and medial–lateral axes was greater when vision was occluded. The anterior or posterior COPpeak was also greater when vision was occluded. The leftward COPpeak was greater when the tactile sensation of the sole was masked. Visual occlusion decreased the tactile perception threshold of the sole. There was no significant interaction between the effect of vision and that of tactile sensation on body sway during quiet stance. [Conclusion] Vision plays a role in returning the body to the neutral position, particularly in the anterior–posterior axis. Tactile sensation contributes particularly to recovery from the leftward body sway during quiet stance. Tactile sensitivity is enhanced by visual occlusion through inter-modal reweighting. However, inter-modal reweighting between vision and tactile sensation is not specifically for postural control during quiet stance.

Key words: Vision, Tactile sensation, Inter-modal reweighting

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INTRODUCTION

Vision, proprioception, tactile sensation and vestibular sensation play a role in postural control in the quiet stance[1)]. In particular, the contribution of vision to postural control in the quiet stance has been thoroughly investigated by testing the effect of visual occlusion. For example, visual occlusion increased the displacement of the center of pressure (COP) in stance[2–4)]. The sway of the lower legs was greater when vision was occluded[5)]. The anterior–posterior body sway with visual occlusion was greater than without visual occlusion[6, 7)]. Postural stability was weaker[8)] and the center of the gravity sway area was greater[9)] when vision was occluded.

The body sway in the anterior–posterior axis is mainly controlled by the ankle, and in the medial-lateral axis it is controlled by the hip[10)]. Thus, the effect of visual occlusion on the body sway in the anterior–posterior axis may be different from the effect in the medial–lateral axis in the quiet stance. Indeed, several studies reported a greater effect of visual occlusion on body sway in the anterior–posterior axis compared with the medial–lateral axis. For example, the standard deviation of the anterior–posterior sway of the waist and legs with visual occlusion was greater than without visual occlusion, but this difference was absent in the medial–lateral axis[6)]. Similarly, the standard deviation of the COP and center of mass displacement in the anterior–posterior axis in standing with visual occlusion was greater than without visual occlusion, but this significant effect was absent in the medial–lateral axis[2)]. Spectral median frequency of the COP oscillation especially in the

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anterior-posterior axis was reduced by vision in stance11). Based on these previous findings, we established our hypothesis 1 that vision plays a role in reducing body sway in the anterior–posterior axis in the quiet stance.

The likely explanation for the increase in body sway induced by visual occlusion is that the return of the swayed body to the neutral position is delayed due to a lack of visual feedback. To elucidate this view, in the present study, our original measurement, the peak COP displacement from the neutral position (COPpeak), was calculated. The COPpeak is the mean distance between the neutral COP and the COP at the peak deviated position. This measurement indicates how quickly humans initiate the sway of the body back to the neutral position. Thus, the COPpeak likely increases with visual occlusion if vision plays a role in the recovery of body sway in the quiet stance (hypothesis 2).

The other purpose of the present study was to elucidate whether inter-modal reweighting between vision and tactile sensation of the sole occurs for the postural control in quiet stance. Sensory weights vary as functions of environmental conditions for balance control in stance12). According to previous studies in blind patients, the long-term absence of vision enhances the reliance of motor control on proprioception13, 14). Loss of auditory cues increased the reliance of postural control on vision in the quiet stance15). Those findings are likely explained by inter-modal reweighting between vision and the other modalities of sensation12, 16–18).

There are several findings suggesting that visual occlusion increases the contribution of somatosensation on the reduction in body sway in the quiet stance. For example, the COP area and velocity were increased by local anesthesia in the forefoot sole in the quiet stance with visual occlusion, whereas such changes were not present when vision was not occluded19). When somatosensation below the ankle is masked in the quiet stance on a small support surface, the COP displacement and velocity increased with visual occlusion, but this effect was absent without visual occlusion20). Based on these previous findings, we hypothesized that the contribution of tactile sensation on the reduction in body sway in the quiet stance is greater when vision is occluded due to inter-modal reweighting between vision and tactile sensation (hypothesis 3). If this hypothesis is true, then the effect of masking the tactile sensation on body sway in the quiet stance must be greater when vision is occluded.

Additionally, we tested whether the effect of masking tactile sensation in the sole on tactile sensitivity is influenced by visual occlusion. In this study, we tested this effect both in sitting without feet on the ground and in the quiet stance. Tactile sensation participates in postural control in the quiet stance, but does not participate in sitting without the feet on the ground. We hypothesized that tactile sensitivity increases with visual occlusion, particularly in the quiet stance, if inter-modal reweighting between vision and tactile sensation contributes to the control of quiet stance posture in particular (hypothesis 4).

There are patients with postural control deficits in stance. For example, in hemiplegic and paraplegic patients, lateral and forward shift of the center of pressure was observed21). In stroke patients, ability of shifting the weight in the paretic side is lower than the non-paretic side22). Postural control deficit is one main target of physical therapy interventions. The present study contributes to the use of vision and tactile sensation on prospective intervention in patients with postural control deficits.

PARTICIPANTS AND METHODS

Sixteen healthy males aged 29.7 ± 7.1 years participated in this study. There are gender differences in physical characteristics23) and motor performance24). To exclude the variability of postural responses caused by gender difference, only males were recruited. All participants had no history of neurological or musculoskeletal diseases. Written consent was obtained from all participants. The experiment was conducted according to the Declaration of Helsinki and was approved by the ethics committee of Osaka Prefecture University (Approval number: 2019-112). Two participants were left-footed, thirteen participants were right-footed, and one participant was mixed-footed, according to the revised version of the Waterloo Footedness Questionnaire25, 26).

A gravicorder (1G06/I-B, Nihon Denshi Sanei, Tokyo, Japan) measuring the COP was placed under the feet. Analog signals from the gravicorder were converted to digital signals at a sampling rate of 100 Hz using an A/D converter (Power Lab 800S; AD Instruments, Colorado Springs, CO, USA), and the digital signals were stored on a PC. A geometric pattern 80 cm in height and 150 cm wide was presented on a vertical wall 1 m in front of the participants. The participants wore liquid crystal goggles to occlude their vision (T.K.K.2275; Takei Kiki, Tokyo, Japan). Earplugs were inserted into the ear canal to block out the auditory noise. Stimulation electrodes were placed 2 cm apart over the medial arch of each sole.

The tactile perceptual threshold was measured both in sitting and in the quiet stance. In sitting, the participants had a seat over the table 70 cm in height. The feet were completely off the ground. In the quiet stance, the participants remained standing with the arms hanging by their side and feet side-by-side with both big toes 6 cm apart. To determine the tactile perceptual threshold, electrical stimulation was applied to the skin over the medial arch of the sole using an electrical stimulator (SS-104 J; Nihon Kohden, Tokyo, Japan) attached to isolators (SS-202 J; Nihon Kohden). The stimulation frequency was 200 Hz with each pulse lasting 1 ms. The intensity of the stimulus was increased gradually, and the participants answered when they perceived the tactile sensation. The tests with and without visual occlusion were alternately conducted, and a pair of the tests was repeated five times. The mean minimum stimulation intensity at which the participants perceived tactile sensation was considered to be the stimulation intensity at the tactile perceptual threshold.

To test the effect of vision, all the participants maintained the quiet stance on the gravicorder. The arms of each participant were beside their trunk, and they viewed a geometric pattern in front of them. A trial with visual occlusion and another without visual occlusion were alternately conducted six times. Thus, the total number of trials was 12. The glass of the liquid glass goggles was opaque in the trials with visual occlusion, but was transparent in the trials without visual occlusion. Each trial lasted for 25 s. The interval between the trials was 1 min. The order of the visual conditions, whether the trial with visual occlusion was conducted first or not, was counterbalanced across the participants.

To test the effect of vision and masking tactile sensation, the participants maintained the quiet stance on the gravicorder for 25 s in each trial. Two sessions were conducted; a session with visual occlusion and a session without visual occlusion. The glass of the liquid glass goggles was opaque in the session with visual occlusion, but was transparent in the session without visual occlusion. The participants were informed of the visual condition before beginning each session. The order of the two sessions was counterbalanced across the participants. In each session, a pair of trials, a trial with masking tactile sensation and another trial without masking, was repeated six times. Thus, the number of the trials was 12 in each session. The interval between the trials was 1 min. Electrical stimulation was administered over the sole to mask the tactile sensation. The stimulus intensity was 1.1 times the tactile perceptual threshold. The condition of the masking tactile sensation was described to the participants before beginning each trial.

The data in the time window from 3 s after the start of the trial to 2 s before the end of the trial were analyzed. Thus, the duration of the data analyzed was 20 s. COPx represents the COP in the medial-lateral axis, COPy represents the COP in the anterior-posterior axis, and COPxy represents the COP on the two-dimensional surface over the anterior–posterior and medial–lateral axes. The total distance of the COP displacement was calculated (COP displacement). The COPpeak was calculated as follows. Firstly, the mean COP, indicating the neutral COP position, was calculated. Secondly, the turning points between the COP displacement directing away from the neutral COP position and towards the neutral position were determined in each direction (peak COPs). Thirdly, the distance between each peak COP and neutral COP was calculated. Finally, all the distances in the time window were averaged (COPpeak). The electrical stimulus intensity at the perceptual threshold with visual occlusion was divided by that without visual occlusion to calculate the threshold ratio, indicating the change in the tactile sensitivity induced by visual occlusion.

A paired t-test was conducted to test the difference between the two means. One sample t-test was conducted to determine whether the threshold ratio was significantly different from 1.0. A repeated measures two-way analysis of variance (ANOVA) was conducted to test the two main effects (the effect of vision and that of masking tactile sensation). The result of Greenhouse–Geisser's correction was reported whenever Mauchly's test of sphericity was significant. The alpha level was 0.05. All the statistical analyses were carried out using Excel Tokei ver. 3.20 (Social Survey Research Information, Tokyo, Japan). All the data in the Results were expressed as the mean and standard error of mean.

RESULTS

The effect of visual occlusion on the COP displacement and COPpeak is shown in Table 1. The COP displacement was significantly greater when vision was occluded in both axes ($p<0.05$). The forward and backward COPpeak was significantly greater when vision was occluded ($p<0.05$). By contrast, the leftward and rightward COPpeak was not significantly different between the visual conditions.

The threshold ratio is shown in Table 2. In both the left and right soles, the threshold ratio, the threshold intensity in the trials with visual occlusion divided by the intensity in the trials without visual occlusion, was significantly smaller than 1.0 in both the quiet stance and sitting ($p<0.05$; one-sample t-test), indicating that tactile sensitivity was enhanced by visual occlusion. The ANOVA failed to reveal a significant effect of the side ($F_{1,15}=1.857$, $p=0.193$, $\eta^2p=0.110$) or position ($F_{1,15}=3.933$, $p=0.066$, $\eta^2p=0.208$) on the ratio without a significant interaction between the main effects ($F_{1,15}=0.135$, $p=0.718$, $\eta^2p=0.009$).

Table 1. Visual effect on COP displacement and COPpeak

	Without VO (cm)	With VO (cm)
COP displacement		
COPx	13.63 (1.12)	17.14 (1.47)*
COPy	12.92 (1.18)	16.17 (1.30)*
COPxy	20.97 (1.75)	26.41 (2.03)*
COPpeak		
Leftward	0.44 (0.04)	0.47 (0.03)
Rightward	0.44 (0.05)	0.47 (0.03)
Forward	0.37 (0.04)	0.42 (0.03)*
Backward	0.36 (0.03)	0.41 (0.03)*

COP: center of pressure; VO: visual occlusion. Mean (standard error).
*p<0.05 (without VO vs. with VO).

Table 2. Threshold ratio

	Left foot	Right foot
Standing	0.98 (0.00)*	0.98 (0.00)*
Sitting	0.99 (0.01)*	0.99 (0.00)*

VO: visual occlusion.
Threshold ratio: threshold intensity with VO/threshold intensity without VO.
Mean (standard error).
*p<0.05 (vs. 1.0, one sample t-test).

The effect of vision and masking tactile sensation on the COP displacement is shown in Table 3. A significant main effect of neither vision (F1,15=2.995, p=0.104, η^2p=0.166) nor masking tactile sensation (F1,15=0.888, p=0.361, η^2p=0.056) was found on the COPx without a significant interaction (F1,15=0.061, p=0.807, η^2p=0.004). A significant main effect of neither vision (F1,15=0.416, p=0.529, η^2p=0.027) nor masking tactile sensation (F1,15=0.931, p=0.350, η^2p=0.058) was found on the COPy without a significant interaction (F1,15=0.441, p=0.517, η^2p=0.029). A significant main effect of neither vision (F1,15=1.493, p=0.241, η^2p=0.091) nor masking tactile sensation (F1,15=1.410, p=0.254, η^2p=0.086) was found on the COPxy without a significant interaction (F1,15=0.168, p=0.688, η^2p=0.011).

The effect of vision and masking tactile stimulation on the COPpeak is shown in Table 4. The COPpeak of the leftward body sway with masking tactile sensation was significantly greater than that without masking (F1,15=5.414, $p<0.05$, η^2p=0.265). There was neither a significant main effect of vision (F1,15=0.231, p=0.638, η^2p=0.015) nor a significant interaction between the main effects (F1,15=0.342, p=0.567, η^2p=0.022). In the rightward direction of the COPpeak, neither a significant main effect of vision (F1, 15=0.167, p=0.689, η^2p=0.011) nor a masking tactile sensation (F1,15=0.308, p=0.587, η^2p=0.020) was revealed without a significant interaction between the main effects (F1,15=0.937, p=0.349, η^2p=0.059). In the forward direction, a significant main effect neither of vision (F1,15=0.920, p=0.352, η^2p=0.058) nor of masking tactile sensation (F1,15=0.020, p=0.891, η^2p=0.001) was revealed without a significant interaction between the main effects (F1,15=0.559, p=0.466, η^2p=0.036). In the backward direction, a significant main effect neither of vision (F1,15=0.314, p=0.584, η^2p=0.020) nor of masking tactile sensation (F1,15=0.389, p=0.542, η^2p=0.025) was revealed without a significant interaction between the main effects (F1,15=0.298, p=0.593, η^2p=0.019).

Table 3. Effect of masking tactile sensation on COP displacement

	Without VO (cm)	With VO (cm)
COPx		
Without M	17.77 (1.97)	19.44 (1.99)
With M	18.25 (2.28)	19.66 (1.82)
COPy		
Without M	19.34 (2.45)	20.41 (2.29)
With M	20.23 (2.97)	20.61 (2.28)
COPxy		
Without M	29.32 (3.34)	31.45 (3.19)
With M	30.37 (4.05)	31.87 (3.11)

COP: center of pressure; VO: visual occlusion; M: masking tactile sensation.
Mean (standard error).

Table 4. Effect of masking tactile sensation on COPpeak

	Without VO (cm)	With VO (cm)	ME
Leftward			
Without M	0.47 (0.04)	0.50 (0.04)	*
With M	0.52 (0.06)	0.52 (0.03)	
Rightward			
Without M	0.51 (0.05)	0.51 (0.04)	
With M	0.50 (0.05)	0.53 (0.04)	
Forward			
Without M	0.47 (0.06)	0.49 (0.06)	
With M	0.46 (0.06)	0.50 (0.06)	
Backward			
Without M	0.46 (0.06)	0.49 (0.06)	
With M	0.49 (0.08)	0.50 (0.05)	

COP: center of pressure; VO: visual occlusion; M: masking tactile sensation.
Mean (standard error).
*$p<0.05$ (ME: main effect of masking tactile sensation).

DISCUSSION

Previous studies reported the greater contribution of vision to body sway in the anterior–posterior axis compared with that in the medial-lateral axis. For example, the standard deviation of the COP in the anterior–posterior axis without visual occlusion was significantly smaller than with visual occlusion, but this significant effect was absent in the medial–lateral axis[2)]. The sway of the trunk and leg without visual occlusion in the anterior–posterior axis was significantly smaller than with visual occlusion, but this significant effect was absent in the medial–lateral axis[6)]. Based on these previous findings, we established our hypothesis 1 that vision contributes to a reduction in body sway, particularly in the anterior–posterior axis. The finding on the COP displacement in this study was not in line with this hypothesis; the increase in the COP displacement induced by visual occlusion occurred both in the anterior–posterior and medial–lateral axes.

In those previous studies, the effect of visual occlusion on body sway in the medial–lateral axis was close to the significant level (p values ranged from 0.06 to 0.08). Thus, inconsistent findings regarding the effect of visual occlusion on body sway in the medial–lateral axis between the previous studies and the present study may be explained by slight differences in the experimental methodology or population of the participants causing slightly different statistical power.

In the study by Dickstein et al., the participants were stroke patients and elderly healthy individuals, and the COP was not measured but the displacements of the waist and leg were measured[6)]. In the previous study by Carpenter et al., the participants maintained the quiet stance on the edge of a support surface, and the position of the feet was restricted within a small surface area[2)]. The postural response to perturbation is dependent on the size of the support surface[27)]; responses occur based on hip strategy when the support surface is small and on ankle strategy when the surface is large. Thus, in this previous study, the postural control strategy for the quiet stance on the edge of the support surface with a strict restriction of the position of the feet within a small area may produce slightly weakened statistical power for testing the data on the effect of vision, leading to an insignificant effect of visual occlusion on COP displacement in the medial–lateral axis.

Visual occlusion increased the COPpeak, particularly in the anterior–posterior axis. The COPpeak represents the magnitude of body sway at the moment at which the recovery of the swayed body back to the neutral position begins. Based on this definition, an increase in the COPpeak means a delayed recovery from body sway. Thus, the present finding supports our hypothesis 2 that vision plays a role in the early recovery of the swayed body to the neutral position in quiet stance.

The effect of visual occlusion on the COPpeak was present only in the anterior–posterior axis. The body sway in the anterior–posterior axis is predominantly controlled by the ankle, and in the medial–lateral axis it is predominantly controlled by the hip in quiet stance[10)]. Thus, the findings may reflect the fact that vision contributes to the ankle motion that mainly controls anterior–posterior body sway.

The effect of visual occlusion on the COPpeak was different from its effect on the COP displacement; the effect of visual occlusion was present on the COP displacement in both the anterior–posterior and medial–lateral axes, but was present on the COPpeak only in the anterior–posterior axis. The COP displacement is calculated by the total sum of the change in the COP position every 10 ms. Thus, the COP displacement reflects how greatly the COP position changes each time. The COPpeak reflects the magnitude between the neutral COP and the COP at the peak deviated position. Thus, the inconsistent findings between the COP displacement and the COPpeak are explained by the view that the change in the COP position each time is greater when vision is occluded regardless of the axis of the displacement, but the recovery from the body sway is earlier for the COP, specifically in the anterior–posterior axis.

The COP area and velocity in the medial–lateral axis increased with local anesthesia of the forefoot sole when vision was occluded, but this effect was absent without visual occlusion[19)]. This indicates that the contribution of tactile sensation on postural control in the quiet stance is enhanced by visual occlusion. There are several findings indicating the reweighting between different modalities of sensation[12, 15–20, 28)]. Based on these findings, we hypothesized that inter-modal reweighting between vision and tactile sensation occurs during postural control in the quiet stance (hypothesis 3). To test the contribution of tactile sensation, local anesthesia or ischemia was used[19, 20)]. In our present study, electrical stimulation was supplied for masking the tactile sensation in the sole. If inter-modal reweighting between vision and tactile sensation contributing to postural control in the quiet stance is present, then the change in body sway induced by masking tactile sensation in the sole in the quiet stance must be greater when vision is occluded.

Masking tactile sensation significantly increased the leftward COPpeak. The COPpeak reflects the moment at which returning the swayed body to the neutral position begins. Accordingly, the present findings mean that the recovery from the leftward body sway is delayed by masking tactile sensation. Nevertheless, neither a significant effect of vision nor a significant interaction between the effect of masking tactile sensation and that of vision was found. Thus, tactile sensation in the sole contributes particularly to the earlier recovery from leftward body sway, although vision does not influence this contribution. These findings indicate that the contribution of tactile sensation to the reduction in body sway in the quiet stance is independent from vision; hypothesis 3 was not supported.

There is an asymmetry between the anticipatory postural adjustment during gait initiation with the left leg and with the right leg[29)]. The present findings indicate that the role of tactile sensation in the sole, particularly for leftward body sway, may reflect this asymmetry in the postural adjustment process in the quiet stance.

We hypothesized that tactile sensitivity in the sole is greater when vision is occluded through inter-modal reweighting between vision and tactile sensation (hypothesis 4). The tactile perceptual threshold was significantly lower when vision was occluded, indicating greater tactile sensitivity during visual occlusion. Thus, hypothesis 4 was supported. This decrease in the threshold occurred both in sitting and in standing. When the participants adopted a sitting position, the feet were in the air without touching the ground, indicating that tactile sensation in sole did not participate in postural control in this position. The effect of visual occlusion on the tactile sensitivity did not significantly interact with the effect of the position. These findings mean that the facilitation of tactile sensation induced by visual occlusion occurs regardless of whether tactile sensation in the sole participates in postural control or not. Thus, the role of the increase in tactile sensitivity induced by visual occlusion, indicating inter-modal reweighting between vision and tactile sensation, may not be specifically aimed at controlling posture in the quiet stance.

In conclusion, vision contributes to a reduction in body sway in both the anterior–posterior and medial–lateral axes in the quiet stance. Main novel findings in this study were the effect of vision and tactile sensation on the returning the swayed body to the neutral position. Vision plays a role in returning the swayed body back to the neutral position, particularly in the anterior–posterior axis. Tactile sensation contributes to earlier recovery from leftward body sway in the quiet stance, but this effect is not influenced by visual occlusion. There is no significant interaction between the effect of vision and that of masking tactile sensation on body sway in the quiet stance. Tactile sensitivity is greater during visual occlusion regardless of whether tactile sensation in the sole participates in postural control. This indicates that inter-modal reweighting between vision and tactile sensation is present, but this mechanism is not specific to postural control in the quiet stance. The present findings contribute to the use of tactile stimulation and vision for the prospective interventions in patients with postural control deficits.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

REFERENCES

1) Fitzpatrick R, McCloskey DI: Proprioceptive, visual and vestibular thresholds for the perception of sway during standing in humans. J Physiol, 1994, 478: 173–186. [Medline] [CrossRef]
2) Carpenter MG, Frank JS, Silcher CP, et al.: The influence of postural threat on the control of upright stance. Exp Brain Res, 2001, 138: 210–218. [Medline] [CrossRef]
3) Schmid M, Nardone A, De Nunzio AM, et al.: Equilibrium during static and dynamic tasks in blind subjects: no evidence of cross-modal plasticity. Brain, 2007, 130: 2097–2107. [Medline] [CrossRef]
4) Sarabon N, Rosker J, Loefler S, et al.: The effect of vision elimination during quiet stance tasks with different feet positions. Gait Posture, 2013, 38: 708–711. [Medline] [CrossRef]
5) Fitzpatrick R, Rogers DK, McCloskey DI: Stable human standing with lower-limb muscle afferents providing the only sensory input. J Physiol, 1994, 480: 395–403. [Medline] [CrossRef]
6) Dickstein R, Abulaffio N: Postural sway of the affected and nonaffected pelvis and leg in stance of hemiparetic patients. Arch Phys Med Rehabil, 2000, 81: 364–367. [Medline] [CrossRef]
7) Butler AA, Lord SR, Rogers MW, et al.: Muscle weakness impairs the proprioceptive control of human standing. Brain Res, 2008, 1242: 244–251. [Medline] [CrossRef]
8) Palm HG, Strobel J, Achatz G, et al.: The role and interaction of visual and auditory afferents in postural stability. Gait Posture, 2009, 30: 328–333. [Medline] [CrossRef]
9) Kanegaonkar RG, Amin K, Clarke M: The contribution of hearing to normal balance. J Laryngol Otol, 2012, 126: 984–988. [Medline] [CrossRef]
10) Winter DA, Prince F, Sterior P: Medial-lateral and anterior-posterior motor responses associated with center of pressure changes in quiet standing. Neurosci Res Commun, 1993, 12: 141–148.
11) Sozzi S, Nardone A, Schieppati M: Specific posture-stabilising effects of vision and touch are revealed by distinct changes of body oscillation frequencies. Front Neurol, 2021, 12: 756984 [CrossRef]. [Medline]
12) Peterka RJ: Sensory integration for human balance control. Handb Clin Neurol, 2018, 159: 27–42. [Medline] [CrossRef]
13) Yoshimura A, Matsugi A, Esaki Y, et al.: Blind humans rely on muscle sense more than normally sighted humans for guiding goal-directed movement. Neurosci Lett, 2010, 471: 171–174. [Medline] [CrossRef]
14) Ozdemir RA, Pourmoghaddam A, Paloski WH: Sensorimotor posture control in the blind: superior ankle proprioceptive acuity does not compensate for vision loss. Gait Posture, 2013, 38: 603–608. [Medline] [CrossRef]
15) Maheu M, Sharp A, Landry SP, et al.: Sensory reweighting after loss of auditory cues in healthy adults. Gait Posture, 2017, 53: 151–154. [Medline] [CrossRef]
16) Peterka RJ: Sensorimotor integration in human postural control. J Neurophysiol, 2002, 88: 1097–1118. [Medline] [CrossRef]
17) Maurer C, Mergner T, Peterka RJ: Multisensory control of human upright stance. Exp Brain Res, 2006, 171: 231–250. [Medline] [CrossRef]
18) Assländer L, Peterka RJ: Sensory reweighting dynamics following removal and addition of visual and proprioceptive cues. J Neurophysiol, 2016, 116: 272–285. [Medline] [CrossRef]
19) Meyer PF, Oddsson LI, De Luca CJ: The role of plantar cutaneous sensation in unperturbed stance. Exp Brain Res, 2004, 156: 505–512. [Medline] [CrossRef]
20) Wang TY, Lin SI: Sensitivity of plantar cutaneous sensation and postural stability. Clin Biomech (Bristol, Avon), 2008, 23: 493–499. [Medline] [CrossRef]
21) Nardone A, Galante M, Lucas B, et al.: Stance control is not affected by paresis and reflex hyperexcitability: the case of spastic patients. J Neurol Neurosurg

Psychiatry, 2001, 70: 635–643. [Medline] [CrossRef]

22) Eng JJ, Chu KS: Reliability and comparison of weight-bearing ability during standing tasks for individuals with chronic stroke. Arch Phys Med Rehabil, 2002, 83: 1138–1144. [Medline] [CrossRef]

23) Hamill PV, Drizd TA, Johnson CL, et al.: NCHS growth curves for children birth-18 years. Washington DC: Department of Health Education and Welfare, 1977.

24) Thomas JR, French KE: Gender differences across age in motor performance a meta-analysis. Psychol Bull, 1985, 98: 260–282. [Medline] [CrossRef]

25) Elias LJ, Bryden MP, Bulman-Fleming MB: Footedness is a better predictor than is handedness of emotional lateralization. Neuropsychologia, 1998, 36: 37–43. [Medline] [CrossRef]

26) Zverev YP: Spatial parameters of walking gait and footedness. Ann Hum Biol, 2006, 33: 161–176. [Medline] [CrossRef]

27) Horak FB, Nashner LM: Central programming of postural movements: adaptation to altered support-surface configurations. J Neurophysiol, 1986, 55: 1369–1381. [Medline] [CrossRef]

28) Logan D, Kiemel T, Jeka JJ: Asymmetric sensory reweighting in human upright stance. PLoS One, 2014, 9: e100418. [Medline] [CrossRef]

29) Hiraoka K, Hatanaka R, Nikaido Y, et al.: Asymmetry of anticipatory postural adjustment during gait initiation. J Hum Kinet, 2014, 42: 7–14. [Medline] [CrossRef]