Postural responses to vibration at various frequencies of the Achilles tendons and forefoot soles during quiet standing

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Abstract

The purpose of this study was to determine the role of somatosensory input to the sensory reference system during quiet standing. Postural responses to vibration (0.5-mm amplitude, 1–60 Hz) applied to the Achilles tendons and forefoot soles were evaluated. Thirteen young healthy adults who showed backward- and forward-lean responses to vibration at high and low frequencies, respectively, participated as subjects. Backward-lean responses occurred at frequencies ≥29.1 Hz in the Achilles tendons and ≥31.2 Hz in the forefoot soles (defined as B-LF). Forward-lean responses occurred at frequencies ≤10.4 Hz in the Achilles tendons and ≤4.3 Hz in the forefoot soles (F-HF). When vibration was simultaneously applied to the Achilles tendons and forefoot soles at F-HF, no response was induced in 70% of trials. Responses in the remaining 30% of trials were forward lean. Simultaneous vibration of the Achilles tendons and forefoot soles at B-LF induced backward-lean responses in all trials. All postural responses occurred 0.5–3.5 s after vibration onset. These findings suggest that postural responses to high-frequency vibrations occur as a compensatory movement, but postural responses to low-frequency vibrations occur to match the positional information from both locations, meaning a servo control mechanism exists in a quiet standing posture. These postural responses are likely to be executed via the sensory reference system located in the supraspinal nervous system.

Keywords: vibration stimulation; sensory reference frame; postural response; positional perception; triceps surae; forefoot sole

1 Introduction

The perception of standing position involves the integration of sensory information from interoceptors (muscle spindles, tendon organs, and mechanoreceptors of joints and the soles of the feet) and exteroceptors (vestibules and eyes) (Gurfinkel, Levik, Popov, Smetanin, & Shlikov, 1988; Massion, 1992). The sensory reference system located in the supraspinal nervous system is important in the processing of this information (Gurfinkel & Levic, 1991; Kavounoudias et al., 2008). This has been experimentally demonstrated by stimulating the muscle spindle of the triceps surae (Eklund, 1972; Fujiwara, Maeda, & Toyama, 2003) or the mechanoreceptors in the forefoot area of the sole (Kavounoudias, Roll, & Roll, 1998) using vibration instruments. Such vibration stimulation at 60–150 Hz induces backward leaning of the body if the subject is standing with their eyes closed, and the response latencies are longer than those of reflexes. This has been interpreted to mean that sensory information with vibration induces the illusionary perception of forward leaning, and backward leaning occurs as a compensatory response via the sensory reference frame (Fujiwara et al., 2003; Gurfinkel & Levic, 1991; Roll, Kavounoudias, & Roll, 2002; Lackner & Levine, 1979).

The postural response to vibration also indicates that the sensory information that results from vibration of the triceps surae or the sole of the foot is perceived as a deviation from the quiet standing (QS) position. Thus, it is thought that the sensory reference frame is organized on the basis of information obtained in the QS posture, in which the body sways slowly. It has been reported that the center of pressure in the anteroposterior direction (CoPap) moves within ±1 cm (Goshima, 1986) at very low frequencies (<2 Hz) (Fujiwara, Koyama, Ikegami, & Okada, 1982; Njiokiktjien & Rijke, 1972). However the role of sensory information with low frequency vibration has not been investigated in QS.

In a preliminary experiment, we found that a relatively low-frequency vibration to the

Achilles tendons or the forefoot soles induced a forward-lean response, which is the opposite direction to the above-mentioned compensatory response. We presumed that the forward response was not a compensatory response, but was a postural change designed to match the sensory information from the triceps surae and forefoot soles. We hypothesized that in QS, the information from both the triceps surae and the forefoot sole would be equivalently evaluated. This hypothesis predicts that when the sensory information from the either the triceps surae or the forefoot sole slightly increases, the standing position will be adjusted to moderately increase the sensory information from the other part. Thus, when relatively low-frequency vibration is applied simultaneously to both the triceps surae and the forefoot sole, both components of sensory information will be perceived as equal and no postural responses will be induced.

We investigated the postural responses that accompanied vibration of the Achilles tendons and forefoot soles at various frequencies. The working hypotheses were as follows: (1) a forward-lean response would be induced when low-frequency vibration was applied to either the Achilles tendons or the forefoot soles and a backward-lean response would be induced by high-frequency vibration, and (2) no response would be induced when low-frequency vibration was simultaneously applied to the Achilles tendons and the forefoot soles.

2 Methods

2.1 *Subjects*

Sixty-eight healthy young adults (32 men, 36 women) participated in a preliminary experiment in which vibration (60 Hz) was bilaterally applied for 5 s to the Achilles tendons or forefoot soles while the subject was standing with their eyes closed. Sixty-one participants (90%) leaned backwards in response to vibration of the Achilles tendon and 25 (37%) leaned backwards in response to vibration of forefoot soles. Thirteen adults who showed backward- and forward-lean responses to vibration at relatively higher and lower frequencies in 1-60 Hz, respectively, participated as subjects. Their mean ± standard deviation (SD) age, height, weight, and foot length was 24.2 ± 3.7 years, 164.7 ± 6.8 cm, 57.5 ± 9.4 kg, and 24.0 ± 1.2 cm, respectively. None of the subjects had a history of neurological or orthopedic impairment. Informed consent was obtained from all subjects after they had received an explanation of the experimental protocol, which was in accordance with the Declaration of Helsinki and approved by our institutional ethics committee.

2.2 *Apparatus and data recording*

Mechanical vibration was applied to the Achilles tendons and/or the forefoot soles bilaterally through the skin using four vibrators (FS102, Electro-design, Japan; Fig. 1). Vibration frequency was controlled by a sine wave with a 0.5-mm peak-to-peak amplitude from a signal generator (WF1966, NF, Japan). The two vibrators for the Achilles tendons were fixed to a handmade frame located posterior to the subject. The vibrators could be moved freely in three-dimensions on the frame. The head of each vibrator (14 mm × 20 mm × 13mm) was oriented along the sagittal plane and set perpendicularly against the Achilles tendon level with the malleolus medialis. The vibrators were pressed up against the tendons with a force of about 200 g so that they moderately extended the triceps surae during vibration, and were driven at 1–60 Hz. The two vibrators for the forefoot soles were fixed to the anterior part of a plate with a hard surface (length × width, 50 cm × 50 cm). The vibrators could be positioned freely in the mediolateral direction on the plate. The head of each vibrator (12-mm diameter) was attached to a part of metatarsal head area in which maximum pressure was loaded in QS posture. It has been reported that this part of the sole has many mechanoreceptors (Motobe, 1976). The initial height of the heads was the same as that of the plate surface.

A force platform (WA1001, WAMI, Japan) composed of three load cells was set under the plate that contained the vibrators for forefoot soles to determine CoPap. The part of metatarsal head area in which maximum pressure was loaded was identified by a pressure distribution measurement system (RSscan International, Belgium). The spatial resolution of this system was 5.0 mm in the anteroposterior direction and 7.0 mm in the mediolateral direction.

Electromyographic (EMG) activity of the tibialis anterior (TA), medial head of the gastrocnemius (GcM), and soleus (Sol) muscles was recorded bilaterally using surface electrodes (P-00-S, Ambu, Denmark). After shaving and cleaning the skin with alcohol, electrodes were aligned along the long axis of each muscle with an inter-electrode distance of about 3 cm. The input impedance for all electrodes was reduced to $\leq$5 kΩ. Signals from electrodes were amplified (×4000) and band-pass filtered (5–500 Hz) using an amplifier (Biotop 6R12, NEC-Sanei, Japan).

All electrical signals were sent to a computer (EX/522CME3, TOSHIBA, Japan) for subsequent analyses via an A/D converter (ADA16-32/2(CB)F, CONTEC, Japan) with a sampling frequency of 1000 Hz and 16-bit resolution. The CoPap electrical signal was also sent to two other devices: a buzzer generator (HIRUTA, F-H6408) to inform subjects a range of ±1 cm of QS position (Goshima, 1986), and a digital oscilloscope (DS6612, IWATSU, Japan) in order that an investigator may tell subjects CoPap deviation during trials.

2.3 *Procedures*

All measurements were taken while the subjects stood barefoot with the feet parallel and 10 cm apart and the arms relaxed at the sides. Prior to the experiment, subjects stood on the plate for 10 s to enable measurement of pressure distribution and identification of the maximal pressure position in the metatarsal head area. This position was adopted as the stimulation position for the forefoot sole and its mean ± SD was 71.0 ± 4.4% of the foot length from the heel and 49.4 ± 17.6% of the foot width from the medial side of the foot.

CoPap fluctuation while maintaining a QS posture with eyes closed was measured for 10 s, and the mean and SD were calculated. The mean and the mean SD of five measurements were adopted as QS position and SD_{QSP}, respectively.

The experiment consisted of two sessions: 1) separate vibration, and 2) simultaneous vibration. In the separate vibration session, vibration was separately applied to the Achilles tendons or the forefoot soles at various frequencies. The lowest frequency that certainly (in 3/3 trials) induced a backward-lean response (B-LF) and the highest frequency that certainly (in 3/3 trials) induced a forward-lean response (F-HF) was determined for each location. In the simultaneous vibration session, the vibration was simultaneously applied to the Achilles tendons and the forefoot soles at B-LF and F-HF.

In the separate vibration session, the B-LF was identified as follows. The vibration was applied three times at each frequency beginning at 30 Hz and increasing or decreasing in steps of 10 Hz. At each frequency the response was identified as backward lean, forward lean or no response. Then, the B-LF was identified using stimulation frequency increments or decrements of 5, 3, or 1 Hz. Next, the F-HF was identified in the same way. In the simultaneous session, vibration was performed five times at B-LF and F-HF, respectively. However, if same response was observed in the first three consecutive trials, the trial was finished. The order of stimulus location (Achilles tendons and forefoot soles) in the separate session and of stimulus frequency (B-LF and F-HF) in the simultaneous session was randomized across subjects.

In a trial, subjects first maintained the QS posture within a range of ±1 cm of the QS position, which was presented by a buzzer sound, with eyes open for at least 5 s. Next, they closed their eyes and kept maintaining the QS posture for at least 10 s. Then, vibration was applied 5–10 s after cessation of the buzzer sound. For Achilles tendon vibration, the head of vibrators touched the Achilles tendons in the eyes-open period of QS. The subjects were instructed to relax and not to resist any postural responses, and were supported by an investigator either at the manubrium or at the superior angle of the scapula when the CoPap exceeded ±4 SD_{QSP} of the QS position. The vibration was stopped once the subjects were supported, or if a response did not appear within 5 s. All subjects rested while standing for 30 s between trials and rested while seated for 3 min between conditions. Voluntary forward and backward leaning of the body with pivoting at the ankles and eyes closed was repeated a few times between trials to reset the influence of vibration on postural control and prevent habituation to the vibration (Thompson, Bélanger, & Fung, 2007).

2.4 *Data analysis*

CoPap and EMG data were analyzed using signal-processing software (BIMUTAS II, Kissei Comtec, Japan) by investigators who were blinded to the vibration condition. A CoPap deviation of more than QS position + 4 SD_{QSP} was taken as a forward-lean response and a

CoPap deviation of less than QS position – 4 SD_{QSP} was taken as a backward-lean response (Fig. 2). The inflection point of the CoPap deviation was defined as the onset of the postural response. In all backward-lean response trials, the CoPap shifted slightly forward just before leaning backward, and the start point of the backward or forward deflection was regarded as the onset of the postural response (Fujiwara, Kiyota, & Maeda, 2011). The amount of time that elapsed from the start of the vibratory stimulus to postural response onset was defined as postural response onset time.

The EMG data were passed through a 40-Hz high-pass Butterworth filter using the seventh-order method and then full-wave rectified to exclude electrocardiographic and movement artifacts. Backward-lean responses were preceded by an activation of triceps surae (GcM or Sol) and forward-lean responses were preceded by an activation of TA and/or a deactivation of Sol (Fig. 2), as in previous studies (Fujiwara et al., 2011; Kiyota & Fujiwara, 2008; Kurokawa, Fujiwara, & Kiyota, 2013). Activation and deactivation onset was visually determined for each trial, and the amount of time that elapsed from the start of the vibratory stimulus to the onset of EMG change was defined as EMG onset time. The time difference between the EMG onset and the postural response onset was measured (Kurokawa et al., 2013).

2.5 *Statistical analysis*

All data were analyzed using the Shapiro-Wilks test for normality and Levine's test for equality of variance. In the separate vibration session, the effects of stimulation location (Achilles tendons, forefoot soles) and response direction (backward-lean, forward-lean) on postural response onset time were assessed using a two-way repeated-measures analysis of variance (ANOVA). The effect of vibration condition (Achilles tendons only, forefoot soles only, simultaneous vibration of the Achilles tendons and forefoot soles) on the backward-lean response onset time was assessed using a one-way ANOVA. Student's t tests were used to investigate the effect of response direction (backward-lean, forward-lean) on EMG onset time and the time difference between the EMG onset and the postural response onset. The alpha level was set at $p < 0.05$. All data were statistically analyzed using SPSS 14.0J (SPSS Japan, Japan).

3 Results

In the separate vibration session, the B-LF was 29.1 ± 10.2 Hz for the Achilles tendons and 31.2 ±14.2 Hz for the forefoot soles (Fig. 3). The F-HF was 10.4 ± 4.1 Hz for the Achilles tendons and 4.3 ± 5.2 Hz for the forefoot soles (Fig. 3). Simultaneous vibration at F-HF did not induce any postural response in 68.9% trials (Table 1). In the other trials, a forward-lean response was induced. Simultaneous vibration at B-LF induced a backward-lean response in all trials.

Figure 4 shows the postural response onset times. In the separate vibration session, there was a significant effect of response direction ($F_{1, 12} = 23.15$, $p < 0.001$) on postural response onset time but no significant effect of stimulation location and no interaction between the two factors. The onset time of forward-lean responses (Achilles tendons: 2.1 ± 0.8 s; forefoot soles: 2.5 ± 0.9 s) was significantly later than that of backward-lean responses (Achilles tendons: 1.4 ± 0.8 s; forefoot soles: 1.4 ± 0.7 s). The onset time of backward-lean responses in the simultaneous vibration session was not significantly different from that in the separate vibration session.

Activation of GcM and/or SoL occurred just before the onset of backward-lean responses in 75.2% of trials (88/117). Activation of TA or transient deactivation of SoL occurred just before the onset of forward-lean responses in 53.3% of trials (49/92). The EMG onset time was 1.3 ± 0.9 s for backward-lean responses and 2.0 ± 1.0 s for forward-lean responses (t_{135}= 4.54, $p < 0.001$; Fig. 5). The time difference between the EMG onset and the postural response onset was 88 ± 26 ms for backward-lean responses and 152 ± 60 ms for forward-lean responses ($t_{58} = 7.17$, $p < 0.001$; Fig. 6).

4 Discussion

Vibration at a relatively high frequency (≥30 Hz) to the Achilles tendons or the forefoot soles clearly induced a backward-lean response, as reported in previous studies (Eklund, 1972; Fujiwara et al., 2003; Kavounoudias et al., 1998; Roll et al., 1993). This backward-lean response is considered to be a compensatory response to the illusionary perception of a forward lean that occurs via the sensory reference frame (Fujiwara et al., 2003; Gurfinkel & Levic, 1991; Roll et al., 2002; Lackner & Levine, 1979). Simultaneous vibration to the Achilles tendons and the forefoot soles at this high frequency also induced backward-lean responses. The latency of the backward-lean response was similar in the separate and simultaneous vibration sessions, suggesting that the same degree of forward postural disturbance was perceived in both sessions.

Vibration at a relatively low frequency to the Achilles tendons (4–10 Hz) or the forefoot soles (2–4 Hz) induced a forward-lean response. A previous study that applied vibration to the soles of the feet at 20, 40, and 60 Hz reported that the compensatory backward-lean response reduced or disappeared at the lower frequencies (Kavounoudias, Roll, & Roll, 1999), but these authors did not investigate vibration frequencies lower than 20 Hz. The present study is the first to demonstrate that a forward-lean response is induced by low-frequency vibration <20 Hz. To investigate the mechanism of this postural response, the low-frequency vibration was simultaneously applied to the Achilles tendons and the forefoot soles. No postural responses were observed in about 70% of trials. In the remaining 30% of trials, forward-lean responses were observed. Backward-lean responses were never observed. These results suggest that different mechanisms underlie the backward-lean response to high-frequency vibration and the forward-lean response to low-frequency vibration. The response to low-frequency vibration may be caused by a servo-like control mechanism whereby positional information from the triceps surae and forefoot sole are used as a comparative target of each other, in which the standing position started changing to match both information. This hypothesis is supported by the result that no postural response was induced by simultaneous low-frequency vibration to both locations, which suggests that the positional information from both locations had equal weight. It has been reported that main frequency component of postural sway in QS is <2 Hz (Fujiwara et al., 1982; Njiokiktjien & Rijke, 1972). The sensory information that accompanies low-frequency vibration would be similar to that during QS, and may therefore relate to the organization of the sensory reference frame for QS. The forward-lean response observed in some trials would be due to unequal perception of the positional information from the two locations, which may be related to the weighting of sensory information (Collins, Refshauge, Todd, & Gandevia, 2005; Kluzik, Horak, & Peterka, 2005).

All postural responses occurred 0.5–3.5 s after vibration onset. This latency is similar to that previously reported for backward-lean responses (Eklund, 1972; Kavounoudias et al., 1998; Roll et al., 1993). The latency of the primary component of somatosensory cortical evoked potentials is about 40 ms (Dumitru, Kalantri, & Dierschke, 1991). The latency of the stretch reflex in the lower leg muscles is <50 ms for the short component, <100 ms for the middle component, and about 120 ms for the long component (Andersen, Sonnenborg, & Arendt-Nielsen, 1999; Diener & Dichgans, 1986). The postural responses observed in the present study might not be reflex responses, but instead might occur via the sensory reference system located in the supraspinal nervous system. Findings from a previous study using functional magnetic resonance imaging (Kavounoudias et al., 2008) suggested that the brain regions associated with positional perception are located in the inferior parietal lobe, the superior temporal sulcus, the insula, and the cerebellum.

The onset time of forward-lean responses was significantly later than that of backward-lean responses, and the EMG onset was also later. The time difference between the EMG onset and the postural response onset was significantly longer for the forward-lean responses than for the backward-lean responses. These differences in onset times of the forward- and backward-lean responses might be caused by differences in processing times for compensatory and matching responses, differences in sensory receptors of vibration (Ribot-Ciscar, Vedel, & Roll, 1989; Roll, Vedel, & Ribot, 1989), differences in ascending and descending information processing pathways (Gardner & Johnson, 2013), or differences in muscle activation and inhibition for body movements under gravity (Kurokawa et al., 2013). Further studies are needed to investigate these factors in detail.

5 Conclusions

When vibration was applied to Achilles tendons or forefoot soles, backward-lean responses occurred for vibration at high frequencies and forward-lean responses occurred for vibration at low frequencies. It is conceivable that postural responses to relatively high-frequency vibration occur as a compensatory movement, whereas postural responses to relatively low-frequency vibration occur to match the positional information from the Achilles tendons and forefoot soles, meaning a servocontrol exists in a QS posture. These postural control mechanisms likely occurred via the sensory reference system located in the supraspinal nervous system.

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Figure captions

Figure 1. Vibrators for the Achilles tendons and forefoot soles.

Figure 2. Representative waveforms of electromyogram (EMG), the center of pressure in the anteroposterior direction (CoPap) and vibration of the Achilles tendons. B-LF, the lowest vibration frequency that induced a backward-lean response; F-HF, the highest vibration frequency that induced a forward-lean response; TA, tibialis anterior; GcM, medial head of the gastrocnemius; Sol; soleus.

Figure 3. Mean and standard deviation of the lowest vibration frequency that induced a backward-lean response (B-LF; filled circles) and the highest vibration frequency that induced a forward-lean response (F-LF; open circles) when applied to the Achilles tendons (left) and forefoot soles (right). Small circles indicate individual data.

Figure 4. Mean and standard deviation of postural response onset time when vibration was applied to the Achilles tendon only (Separate vibration, Achilles tendon), the forefoot sole only (Separate vibration, Sole), and Achilles tendon and the forefoot sole simultaneously (Simultaneous vibration). B-LF, the lowest vibration frequency that induced a backward-lean response; F-HF, the highest vibration frequency that induced a forward-lean response. **$p < 0.01$.

Figure 5. Mean and standard deviation of EMG onset time. ***$p < 0.001$.

Figure 6. Mean and standard deviation of the time difference between the EMG onset and the

postural response onset. ***$p < 0.001$.

Table 1. Percentage of trials with a postural response in the simultaneous vibration session. F-HF, the highest vibration frequency that induced a forward-lean response; B-LF, the lowest vibration frequency that induced a backward-lean response. The total number of trials was 45 at F-HF and 39 at B-LF. Numbers shown in parentheses indicate the number of subjects.

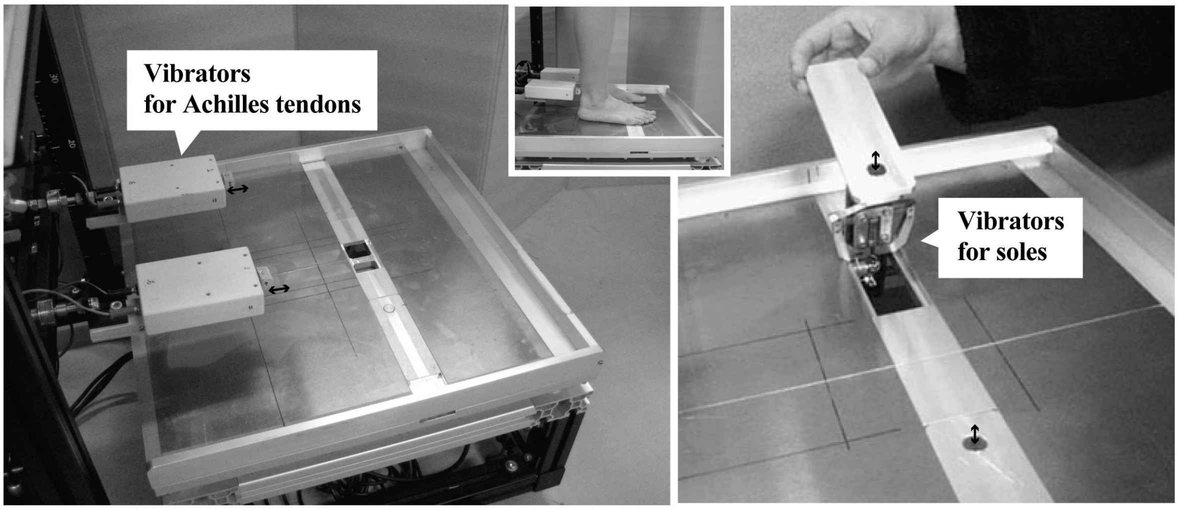
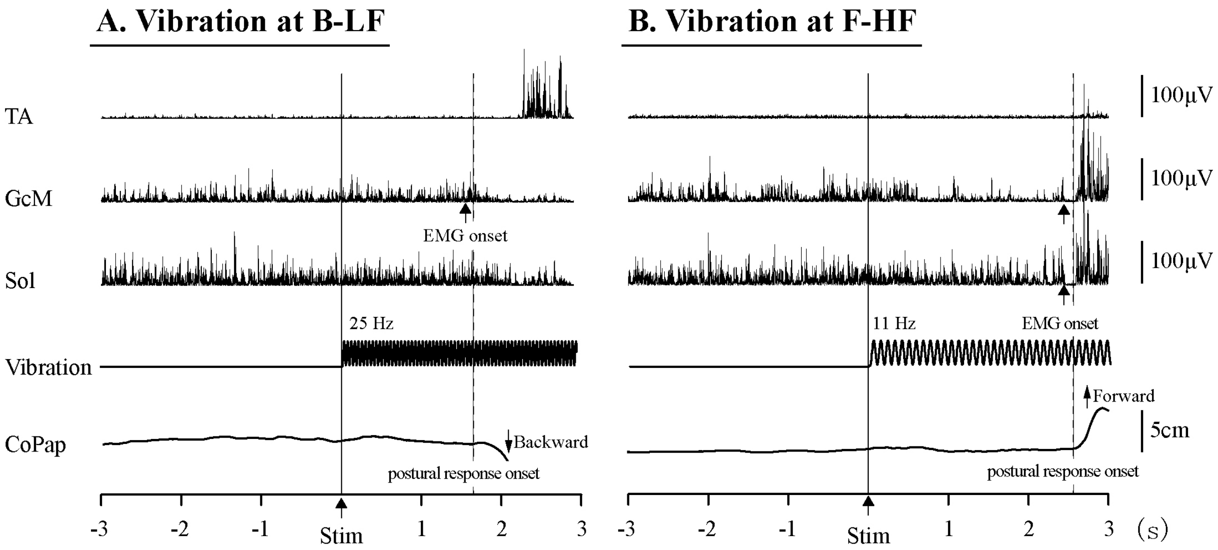
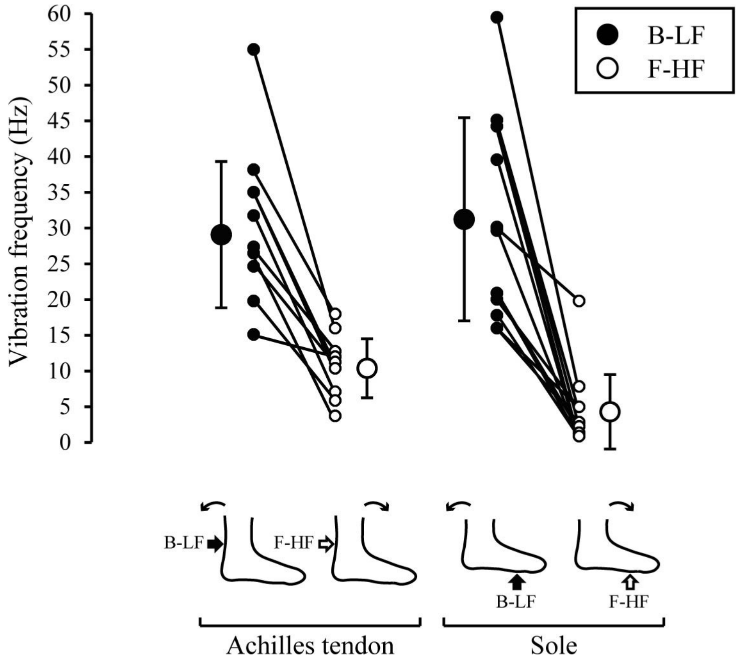


Fig. 1



A. Vibration at B-LF
B. Vibration at F-HF
TA
GcM
Sol
Vibration
CoPap
EMG onset
25 Hz
11 Hz
EMG onset
Backward
Forward
postural response onset
postural response onset
100μV
100μV
100μV
5cm
-3
-2
-1
Stim
1
2
3
-3
-2
-1
Stim
1
2
3
(s)

Fig. 2



Vibration frequency (Hz)
60
55
50
45
40
35
30
25
20
15
10
5
0
B-LF
F-HF
B-LF
F-HF
B-LF
F-HF
Achilles tendon
Sole

Fig. 3

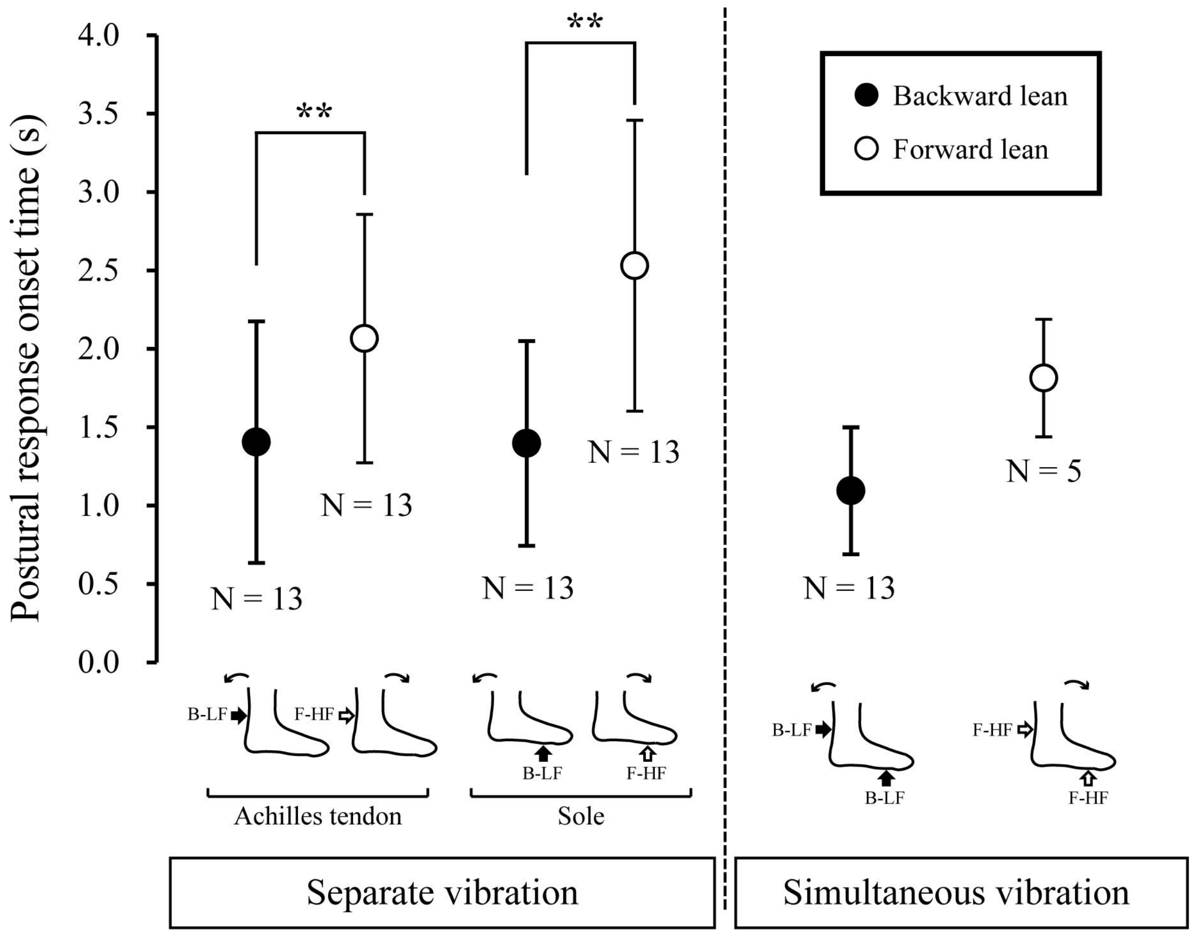

Postural response onset time (s)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
**
**
Backward lean
Forward lean
N = 13
N = 13
N = 13
N = 13
N = 13
N = 5
B-LF
F-HF
B-LF
F-HF
B-LF
B-LF
F-HF
F-HF
Achilles tendon
Sole
Separate vibration
Simultaneous vibration

Fig. 4

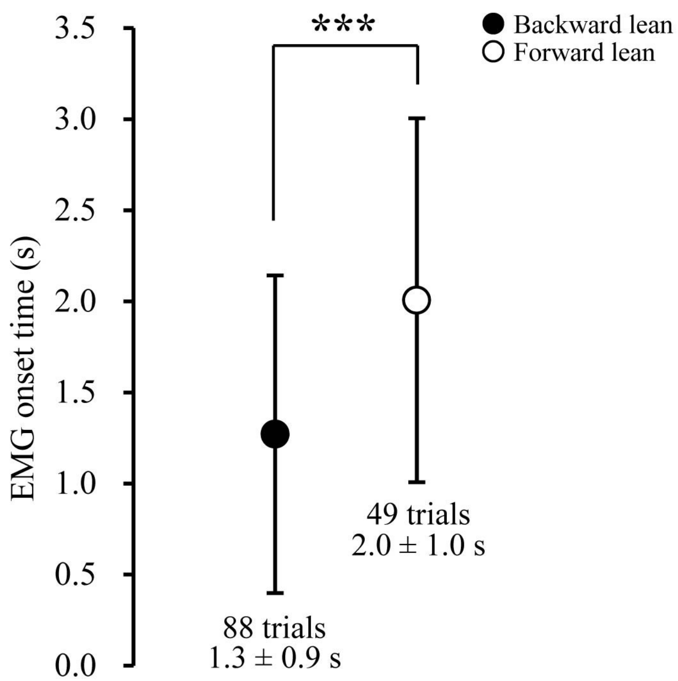

***
Backward lean
Forward lean
EMG onset time (s)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
49 trials
2.0 ± 1.0 s
88 trials
1.3 ± 0.9 s

Fig. 5

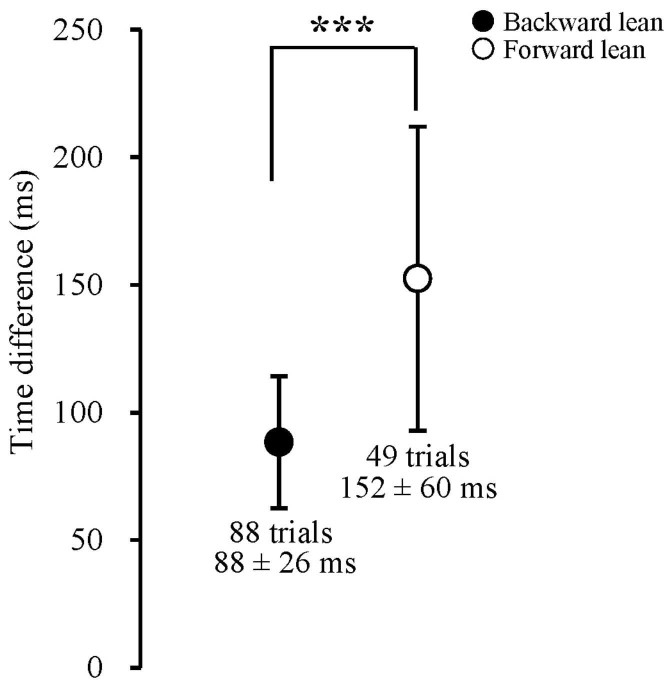

250
200
150
100
50
0
Time difference (ms)
***
Backward lean
Forward lean
49 trials
152 ± 60 ms
88 trials
88 ± 26 ms

Fig. 6

Table 1.

Postural response	Simultaneous vibration at F-HF	at B-LF
No response	68.9% (11)	0.0% (0)
Forward-lean response	31.1% (5)	0.0% (0)
Backward-lean response	0.0% (0)	100% (13)

F-HF, the highest frequency that induced a forward-lean response; B-LF, the lowest frequency that induced a backward-lean response. Number of total trials was 45 at F-HF and 39 at B-LF. Numbers shown in parentheses indicate the number of subjects.