Postural responses accompanying Achilles tendon vibration stimulation during various phases of sit-to-stand movement

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Abstract

The aim of this study was to determine the postural response accompanying Achilles tendon vibration stimulation during various phases of the sit-to-stand movement. Twelve healthy young adults performed the sit-to-stand movement in response to an auditory signal 2 s after a first one. Vibration stimulation with a 100-Hz frequency was applied to both Achilles tendons during the following phases: (1) 10-s of sitting before standing up; (2) 10-s plus a period until the standing position was achieved and (3) 5-s after standing. The postural response after standing was analyzed with the center of foot pressure in the anteroposterior direction. Forward leaning responses were identified in 78.3% and 63.3% of trials under conditions (1) and (2), respectively. Backward leaning responses were identified in 93.3% of the trials under condition (3). Response latency (± standard deviation (SD)) was significantly longer under conditions (1) and (2) than under condition (3) (872 ± 576 and 1026 ± 542 vs. 555 ± 322 ms; *ps* < 0.05). Sensory information at the standing point might be anticipated based on sensory information received while sitting. Consequently, postural response as a compensatory movement would occur via the sensory reference system within the supraspinal nervous system.

Keywords: Sit-to-stand; vibration stimulation; sensory reference frame; postural response; positional perception; Triceps Surae

1 Introduction

Schmidt (1975) proposed a motor schema in which response specification for executing a motor program is generated, and the sensory consequences induced by the movement are anticipated just before starting the movement. The sensory consequence is thought to be compared with actually generated information via the sensory reference frame (Schmidt 1975; Lestienne and Gurfinkel 1988; Roll et al 1989). This concept could be applied to the perception of standing after a transient movement.

The sit-to-stand movement is frequently performed during the day (McLeod et al 1975; Dall and Kerr 2010). This movement could be regarded as a postural change from sitting to standing, which is a type of transient movement (Brooks 1986). Given the above hypothesis, sensory information obtained while sitting before a postural change would affect standing posture after the change. This has been experimentally demonstrated by stimulating the Achilles tendons using vibration. Such vibration stimulation with 70 – 150 Hz induces the body to lean backwards while standing with the eyes closed (Eklund 1972; Roll et al. 1993; Fujiwara et al. 2003; Thompson et al 2011; Mohapatra et al 2012). This phenomenon has been interpreted to mean that sensory information from the vibration induces the illusionary perception that the body is leaning forward, so that backward leaning occurs as a compensatory response. This suggests that the sensory information from the Triceps Surae muscle is important for positional perception while standing, and that the compensatory postural response is executed based on this sensory information. When vibration stimulation is applied to the Achilles tendon before starting the sit-to-stand movement, the sensory information from the Triceps Surae at the point of standing up is presumed to be anticipated and compared with the actual response. Consequently, the compensatory postural response would be induced.

The hypothesis that the present study tested was that during the sit-to-stand movement, sensory information at the standing point would be anticipated based on sensory information received until the movement started, and that the standing position would be perceived by comparing the anticipated with the actual information. Vibration stimulation was applied to the Achilles tendons during various phases of the sit-to-stand movement, and postural responses accompanying the stimulation were investigated. The working hypotheses were as follows: (1) forward leaning would be induced as compensatory response when vibration is applied only during sitting; (2) the compensatory forward-leaning response would be induced without the vibration effect during the transition until standing upright, and (3) backward leaning would be induced when the vibration is applied after standing upright.

2 Methods

2.1 *Design*

To experimentally prove the hypothesis, vibration was applied to the Achilles tendons as follows: (1) while sitting, before starting the sit-to-stand movement; (2) until the standing position was reached, including sitting; and (3) after reaching the standing position. The hypothesis would be proven if the forward leaning response was observed under conditions 1) and 2), in contrast to backward leaning under condition 3).

2.2 *Participants*

Sixteen healthy adults (7 men, 9 women) participated in three preliminary trials, during which vibration (100 Hz) was applied for 5 s to both Achilles tendons while standing with their eyes closed. Twelve participants (5 men and 7 men) leaned backward in all trials and were thus selected for the present study. The mean ± standard deviation (SD) of age, height, weight, and foot length was 26.8 ± 5.9 years, 164.5 ± 7.1 cm, 58.5 ± 8.9 kg and 24.3 ± 1.3 cm, respectively. None of the participants had a history of neurological or orthopedic impairment. Written, informed consent was obtained from all participants after receiving an explanation of the experimental protocol, which was in accordance with the declaration of Helsinki and approved by our institutional ethics committee.

2.3 *Apparatus*

The center of pressure in the anteroposterior direction (CoPap) and vertical force (Fz) during the sit-to-stand movement were measured using one force platform for the seat and another for the floor (WJ-1001, WAMI, Japan; length × width, 50 × 50 cm). Both platforms have a hard surface that is not covered with foam. The seat platform was set at the height of the lateral femoral epicondyle from the foot platform during quiet standing (QS) (Fig. 1). The height was regulated by moving the seat up and down using hydraulic equipment. The participants sat with the midpoint between the lateral femoral epicondyle and greater trochanter along the anterior edge of the seat platform. The zero position in the anteroposterior direction on the foot platform was set at 14 cm from the posterior edge and defined as the heel position. The foot platform was moved in the anteroposterior direction to set the angle of the ankle joint at 10° of dorsiflexion.

Electromyographic (EMG) activities of the Tibialis Anterior (TA), Medial head of the Gastrocnemius (GcM) and Soleus (Sol) on the right side were recorded 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 the electrodes was reduced to ≤ 5 kΩ. Signals from electrodes were amplified (× 4000) and band-pass filtered (5 – 500 Hz) using an amplifier (Biotop 6R12, NEC-Sanei, Japan).

Mechanical vibration was applied to the Achilles tendons bilaterally through the skin using two vibrators (TMT-18, Heiwa Electrical Industrial Co., Japan). Each vibrator was independently strapped to the ankle region with a rubber belt. The vibration frequency was set at 100 Hz with a 1.5-mm amplitude as previously described (Fujiwara et al 2003). A trigger-delay device (FH-D1, HIRUTA ME, Japan) controlled the start and end of the vibratory stimulation. The onset of vibration was detected by a miniature unidirectional accelerometer (AG-5GB, Kyowa, Japan) attached to each vibrator. A warning stimulus (S1) and a subsequent response stimulus (S2) were presented via earphones using two tone-bursts generated by a function generator (WF1966, NF, Japan). The frequency, duration, and intensity of both auditory stimuli were 2 kHz, 100 ms, and 60 dB, respectively, and the S1-S2 interval was set at 2 s.

All electrical signals were sent for subsequent analyses to a computer (M533MS, Iiyama, Japan) via an A/D converter (ADA16-32/2(CB)F, CONTEC, Japan) with a sampling frequency of 1000 Hz and 16-bit resolution. A CoPap electrical signal was sent to another computer (PC9801BX, NEC, Japan) via an A/D converter (PIO9045, IO-Data, Japan) with a 20-Hz sampling rate and 12-bit resolution. A buzzer sounded when the CoPap was located within a specific range to inform the participants of their QS position. The buzzer sound was turned off before the S1 onset (Fig. 2).

2.4 *Test procedures*

All measurements were obtained from the participants while barefoot, with the feet parallel and 10 cm apart, the heels positioned along a line, and the eyes closed. To reduce individual variations in reactive motion of the upper limbs during sit-to-sand movements, the participants crossed their arms so that their forearms were resting on their chest. They sat along the anterior edge of the seat platform with the midpoint between the lateral femoral epicondyle and the greater trochanter. The ankle joint was set at 10° of dorsiflexion. Thus, the duration from sitting to starting knee extension was intermediate between when the heel was just under the hip joint and when the heel was anterior to the joint (Goulart and Valls-Sole 1999; Janssen et al 2002; Jacobs et al 2011). The initial foot and seating positions on the platforms were confirmed using stoppers in each trial.

CoPap fluctuation while maintaining a QS posture was initially measured for 10 s, and the mean position was then calculated. The mean of five measurements was taken as the QS position.

Next, measurement of sit-to-stand movement commenced (Fig. 2). At the start of each trial, the participants maintained the QS posture within a range of ± 1 cm of the QS position for 10 s, and memorized the standing position as the target position after movement. A buzzing sound was generated for the initial 5 s as a cue for the range. The participants were able to hear the buzzer, even if they were wearing earphones. They sat on the platform and maintained a seated posture for 10 s. S1 and S2 auditory stimuli were then delivered at 8 and 10 s. In response to S2, the participants stood up facing the target position. They pressed a switch held in the dominant hand when they perceived that they had become fully upright, and then maintained that position for 5 s. They were then instructed to respond to S2 as rapidly as possible and to stand up at a comfortable speed.

Ten sit-to-stand trials were repeated without vibration (Control) after five initial practices. Correct application of the measurement protocol was confirmed during practice trials. Vibration stimulation was applied next during the following three phases: (1) the 10-s period until movement started (U-MS); (2) the 10-s plus the elapsed time until the participants felt that they had reached the standing position (U-ST); and (3) the 5-s period after they felt that they had reached the standing position (A-ST). The participants did not resist any postural responses and were supported by an investigator either at the manubrium, if their forward lean while standing became extreme, or at the superior angle of the scapula, if their backward lean became extreme. In A-ST, the stimulation was stopped once the response started. Five trials were repeated for each vibration condition, and the order of conditions was randomized for each participant. All participants rested while standing both for 30 s between trials and for 3 min between conditions while seated. Voluntary forward and backward leaning of the body and pivoting at the ankles with 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 et al 2007).

2.5 *Data analysis*

All data were analyzed using signal processing software (BIMUTAS II, Kissei Comtec, Japan) by investigators who were blinded to the conditions. The mean value of the 5-s period during QS without the buzzing sound was measured as the baseline for the

CoPap position in each trial.

The onset of the sit-to-stand movement was identified as the onset of forward CoPap displacement from the seat platform (Fig. 3). The stand-up point in the sit-to-stand movement was defined as the second negative peak point of Fz from the floor platform. Time from movement onset to the stand-up point was calculated as movement time. The CoPap position at the stand-up point (stand-up position) was then measured. The time difference between the stand-up point and the point of perceiving upright posture was defined as the stand-up perception time.

Under control conditions, CoPap after reaching the stand-up position gradually moved backward and stopped around the target position after approximately 3 s (Fig. 3). Therefore, the mean CoPap position from 3 to 4 s after reaching the stand-up position was measured in the control, and the mean (stable standing position (Stable-SP)) and SD among the five trials was calculated. In each trial of the vibration conditions, a CoPap deviation of more than the stable-SP + 2 SD was taken as the forward leaning response, and that of a less than Stable-SP – 2 SD was taken as the backward response (Fig. 4). The start (inflection) point of the CoPap deviation was defined as the postural response onset. In many backward response trials (67%), the body slightly shifted forward just before leaning backward, the start point of which was regarded as the postural response onset. The amount of time that elapsed from the point of stand-up perception to postural response onset was defined as postural response onset time.

The EMGs 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. The GcM was activated, and the Sol was transiently deactivated just before the onset of the backward and forward responses, respectively. Therefore, activation and deactivation onset was visually determined during each trial, and the onset time from the stand-up perception point, as well as the time difference between the onset of the EMG change and CoPap deviation, were measured.

2.6 *Statistical analysis*

All data were analyzed using the Shapiro-Wilks test for normality and Levine’s test for equal variance. The effect of a condition on the movement time between the sit-to-stand and stand-up position was assessed using a one-way repeated-measures analysis of variance (ANOVA). The effect of a condition on the onset time of the sit-to-stand movement and the effect of various vibration conditions on the postural response onset time were assessed using the Friedman and Kruskal-Wallis tests, respectively. Post-hoc multiple-comparison analysis proceeded using the Wilcoxon and Mann-Whitney tests with the Bonferroni alpha level correction. A one-sample t test was used to assess significant differences both between stand-up and target positions and between stand-up and stand-up perception points. Onset times between backward and forward responses, and latencies between EMG activation and deactivation were compared using Student's t test. The significance of trial numbers for forward, backward and absent responses to each vibration condition (3 × 3) was assessed using the chi-square (χ^2) test. Trial numbers among postural responses under each vibration condition and among all vibration conditions in each direction, and the numbers of participants among five trials under each condition and direction of postural response were compared using χ^2 goodness-of-fit test. The magnitude of correlations between the stand-up position and the Stable-SP in the control condition was evaluated using Pearson's correlation coefficient. The alpha level was set at $p < 0.05$. All data were statistically analyzed using SPSS 14.0J (SPSS Japan, Japan).

3 Results

3.1 *Sit-to-stand movement pattern (Fig. 3, 4)*

The onset time of the sit-to-stand movement, movement time and stand-up position did not significantly differ among conditions. The mean values of these parameters among all trials was 168 ± 44 ms, 1672 ± 188 ms and 1.4 ± 1.3 cm, respectively. The stand-up point was significantly anterior to the target position ($t(11) = 3.57$, $p < 0.01$). The elapsed time between the stand-up position and its perception point did not significantly differ among conditions. The mean value among all trials was 99 ± 284 ms and did not significantly differ from zero.

3.2 *Postural responses after reaching the stand-up position with vibration*

The CoPap shifted toward the target position after reaching the stand-up position under control conditions. The Stable-SP position did not significantly differ from the target position (Stable-SP: 0.37 ± 0.6 cm) and did not correlate with the stand-up position.

Table 1 shows the number of participants with postural responses in each trial according to each condition. Inter-trial variations did not significantly differ under each vibration condition. Postural responses after reaching the stand-up position significantly differed according to the vibration conditions ($\chi^2(4) = 137.8$, $p < 0.001$) (Figs. 4 and 5). The forward, backward and no response were identified in 78.3% and 63.3%, 3.3% and 30.0%, and in 18.3% and 6.7%, respectively, of the U-MS and U-ST trials. The backward response and no response were determined in 93.3% and 6.7% of the A-ST trials, respectively. In A-ST condition, none of the trials showed forward response. The number of trials with postural responses under each condition was larger in the order of forward > none > backward in the U-MS trial (*ps* < 0.05), forward > backward > none in the U-ST trial (*ps* < 0.05), and backward > none ~ forward in the A-ST trial (*ps* < 0.001). More trials had postural responses in each direction in the following order: U-MS ~ U-ST > A-ST for a forward lean (*ps* < 0.001) and A-ST > U-ST > U-MS for a backward lean (*ps* < 0.001). The number of trials with no responses significantly differed among conditions.

Figure 6 shows postural response onset times. The mean forward response onset times were 872 ± 576 ms in U-MS and 1026 ± 542 ms in U-ST, and the mean backward response onset time was 555 ± 322 ms in A-ST. The range of onset time was 144 - 3239 ms. Trials that had no or very few forward responses in A-ST and backward responses in U-MS were excluded from the following statistical analysis. Onset time was significantly affected by vibration condition ($\chi^2(2) = 26.2$, $p < 0.001$) (U-MS ~ U-ST > A-ST; *ps* < 0.05). The backward response onset was significantly slower in U-ST than in A-ST ($t(45) = 3.37$; $p < 0.01$).

Activation of the GcM and transient deactivation of the Sol occurred just before the onset of backward and forward responses in 35.5% and 51.8% of the trials with such responses, respectively. The time differences between the onset of the EMG change and the postural response were 94 ± 34 and 243 ± 89 ms, respectively, which were significantly different ($t(60) = 10.03$, $p < 0.001$). The differences in elapsed time between the onset of the EMG change and the perception of stand-up in the backward and forward responses were 539 ± 330 and 545 ± 363 ms, respectively (no significant difference).

4 Discussion

The principal finding of the present study is that when vibration stimulation was applied to both Achilles tendons of a seated participant, a forward leaning response occurred just after reaching the stand-up position. The hypothesis of this study was that sensory information at the standing point would be anticipated, based on received sensory information until the movement started, and that the standing position would be perceived by comparing the anticipated with the actual information. Our findings appear to support this hypothesis. Following the sit-to-stand movement pattern, the postural responses after reaching the stand-up position with vibration are discussed below.

4.1 *Sit-to-stand movement pattern*

Vibration did not significantly affect the sit-to-stand movement patterns (onset time of the movement, movement time, and stand-up position). This indicates that postural responses after reaching the stand-up position could be discussed without respect to movement patterns, and that the Triceps Surae stimulated by vibration would not be an agonist muscle during the sit-to-stand. Reports indicate that the muscles used to execute sit-to-stand movements are the lumbar paraspinal muscles, the quadriceps, and the hamstrings (Goulart and Valls-Sole 1999). On the other hand, sensory information from the Triceps Surae would be closely associated with positional perception after reaching the standing position.

Regardless of the vibration condition, stand-up positions were slightly anterior to the target position, but were located within the CoPap fluctuation range of ± 1 cm (Goshima 1986) during QS. When the sit-to-stand movement was performed on variously inclined support surfaces, including a chair, the trunk was very slightly bent forward after reaching standing, regardless of the inclination conditions, which is consistent with this result. This is due to the forward acceleration required for the sit-to-stand (Hanke et al 1995). In addition, the stand-up and stand-up perception points did not significantly differ, indicating that the participants could precisely perceive the stand-up point. The CoPap gradually moved backward and then located near the target position around 3 s after reaching the stand-up position under control conditions; however, the stable standing position was not significantly affected by the stand-up perception.

4.2 *Postural responses after reaching the stand-up position with vibration*

Participants who leaned backward after vibration was applied to the Achilles tendon during QS were selected for the present study. This is regarded as a compensatory response to the positional perception (forward leaning) elicited by the vibration (Eklund 1972; Roll et al 1993). Our participants probably would have had a frame of reference for comparisons of sensory information from the Triceps Surae with anticipatory information. When vibration was applied just after the stand-up perception, the backward response occurred in 93% of the trials. Vibration stimulation just after the stand-up would act in the same way as stimulation while maintaining the QS posture.

The forward response occurred in 78% of all trials when vibration was applied only until the start of movement. A similar postural response occurred less frequently (63% of all trials) when vibration was applied until the point that stand-up was perceived, indicating that vibration stimulation might be applied occasionally until after reaching standing. Alternatively, sensory information generated during sit-to-stand movement might influence the perception of the stand-up position. Therefore, the actual amount of muscular information from the Triceps Surae at the stand-up point with vibration only during sitting would be much less than the amount of information estimated just before the sit-to-stand, so that it would be perceived to maintain a backward leaning posture. Consequently, a forward leaning compensatory response would be elicited.

Some studies have found that visual (eyes closed, visual motion stimulus) or somatosensory (support inclination, unstable seat) information is manipulated during sit-to-stand movement (Assaiante et al 2011; Kuramatsu et al 2012; Slaboda et al 2012). Most of these studies focused on modulation of the movement by changes in sensory information. On the other hand, Assaiante et al (2011) reported that support inclination does not affect postural stability and orientation while standing after the sit-to-stand movement. Unlike the present study, the support surface in these studies might have remained inclined after standing, which means that both the anticipated information generated during sitting and the actual information generated after standing are consistent.

4.3 *Onset time of postural response after reaching the stand-up position with vibration*

A significant difference was observed in the forward (about 1000 ms) and backward (about 600 ms) response onset times. Furthermore, GcM activity started to increase 94 ms before the onset of the backward response, and Sol activity started to decrease 243 ms before the onset of the forward response. No significant differences were seen in the delay of these EMG onset times to the stand-up perception between the forward and backward responses (545 and 539 ms, respectively). The difference in onset time between the responses was apparently caused by variations in gravitational effect on body movement, as revealed by the muscle activation patterns. The postural response time after vibration to the sole of the foot and lower leg muscle is between 500 ms and 1200 ms (Eklund 1972; Roll et al 1993; Kavounoudias et al 1999), and the latency of the primary component of somatosensory cortical evoked potentials is about 40 ms (Dumitru et al 1991). Latency in the stretch reflex of the lower leg muscles is < 50 ms in the short component, < 100 ms in the middle component, and about 120 ms in the long component (Diener and Dichgans 1986). The compensatory postural response might not be a reflex, but rather might occur via the sensory reference system in the supraspinal nervous system. The findings from a previous study of functional magnetic resonance imaging (Kavounoudias et al 2008) suggest that brain regions associated with positional perception are located in the inferior parietal lobe, the superior temporal sulcus, the insula and the cerebellum.

4.4 *Inter-trial variations in postural responses after reaching the stand-up position with vibration*

The directions of postural responses to the various conditions among trials did not significantly differ. A previous study found that postural responses to stimulation decrease with trial repetition when vibration is applied to the Achilles tendon during bilateral arm movement (Fujiwara et al 2003). Caudron et al (2010) suggest that posture adapts to even relatively small disturbances associated with vibration. The participants in the present study repeated voluntary forward and backward leaning of the body, pivoting at the ankles with their eyes closed a few times between trials. It has been suggested that such active movement would reset or decrease the sensory habituation (Tomassini et al 2012; Thompson et al 2007). In addition, the participants in the present study were directed not to resist any postural responses, and were supported before their standing position exceeded each stability limit (that is, extreme forward or backward leaning). Therefore, the postural responses induced by vibration might not have disturbed these participants. Inter-trial variation in direction of postural response and postural adaptation to stimulation would not occur as a result of these experimental conditions.

4.5 *Study limitations and future studies*

The present study consisted of few trials and a small study cohort. More participants or trials will allow more detailed investigations both of individual differences in postural responses and of different responses according to sit-to-stand movement patterns. The present study focused on sensory information from the Triceps Surae, but similar information from the trunk and thigh muscles might also be important for positional perception while standing.

5. Conclusions

When vibration stimulation was applied to both Achilles tendons while sitting, a forward leaning response occurred immediately after reaching the stand-up position. Sensory information at the stand-up position might be anticipated based on sensory information received during sitting, and the postural response as a compensatory movement would occur via the sensory reference system within the supraspinal nervous system. The present findings suggest the importance of sensory information at initial posture to voluntary movement. Therefore, a new approach that emphasizes sensory information while sitting could be developed to enhance clinical training in sit-to-stand movement.

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Figure captions

Figure 1. Experimental set-up

(A) Seat platform; (B) floor platform; (C) seat height; (D) Tibialis Anterior; (E) Medial head of Gastrocnemius; (F) Soleus; (G) ground; (H) earphone; (I) switch; (J) vibrator. (a) lateral epicondyle; (b) lateral malleolus.

Figure 2. Experimental protocol

(A) Control and (B) vibration conditions. U-MS, until movement starts; U-ST, until perception of reaching standing position; A-ST: after perception of reaching standing position.

Figure 3. Grand average waveforms of CoPap recorded from seat platform, and Fz and CoPap from floor platform under control conditions

Stand-up point is shown as 0 ms.

Figure 4. Representative waveforms of Fz and CoPap from floor platform, and EMG under vibration conditions

Stand-up perception point is shown as 0 ms. (A) U-MS, until movement starts; (B)

U-ST; until perception of reaching standing position; (C) A-ST, after perception of reaching standing position.

Figure 5. Trial rate of postural responses under each vibration condition

U-MS, until movement starts; U-ST, until perception of reaching standing position; A-ST, after perception of reaching standing position.

Figure 6. Mean and standard deviation of postural response onset time

U-MS, until movement starts; U-ST, until perception of reaching standing position; A-ST, after perception of reaching standing position; $*p < 0.05$.

Table 1. Number of participants with postural responses in each trial according to vibration conditions

U-MS, until movement starts; U-ST, until perception of reaching standing position; A-ST, after perception of reaching standing position; $*p < 0.05$, $**p < 0.01$, $***p < 0.001$.

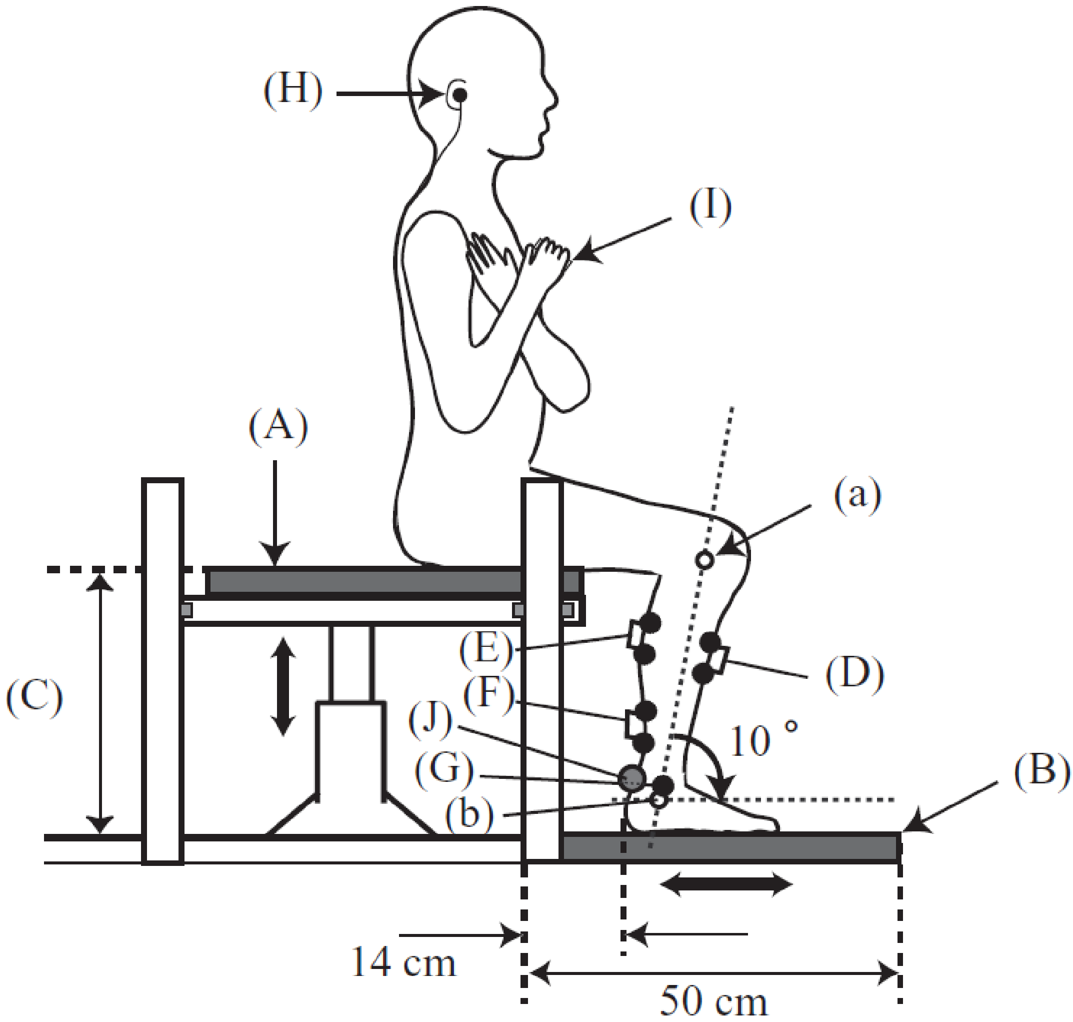


Fig. 1

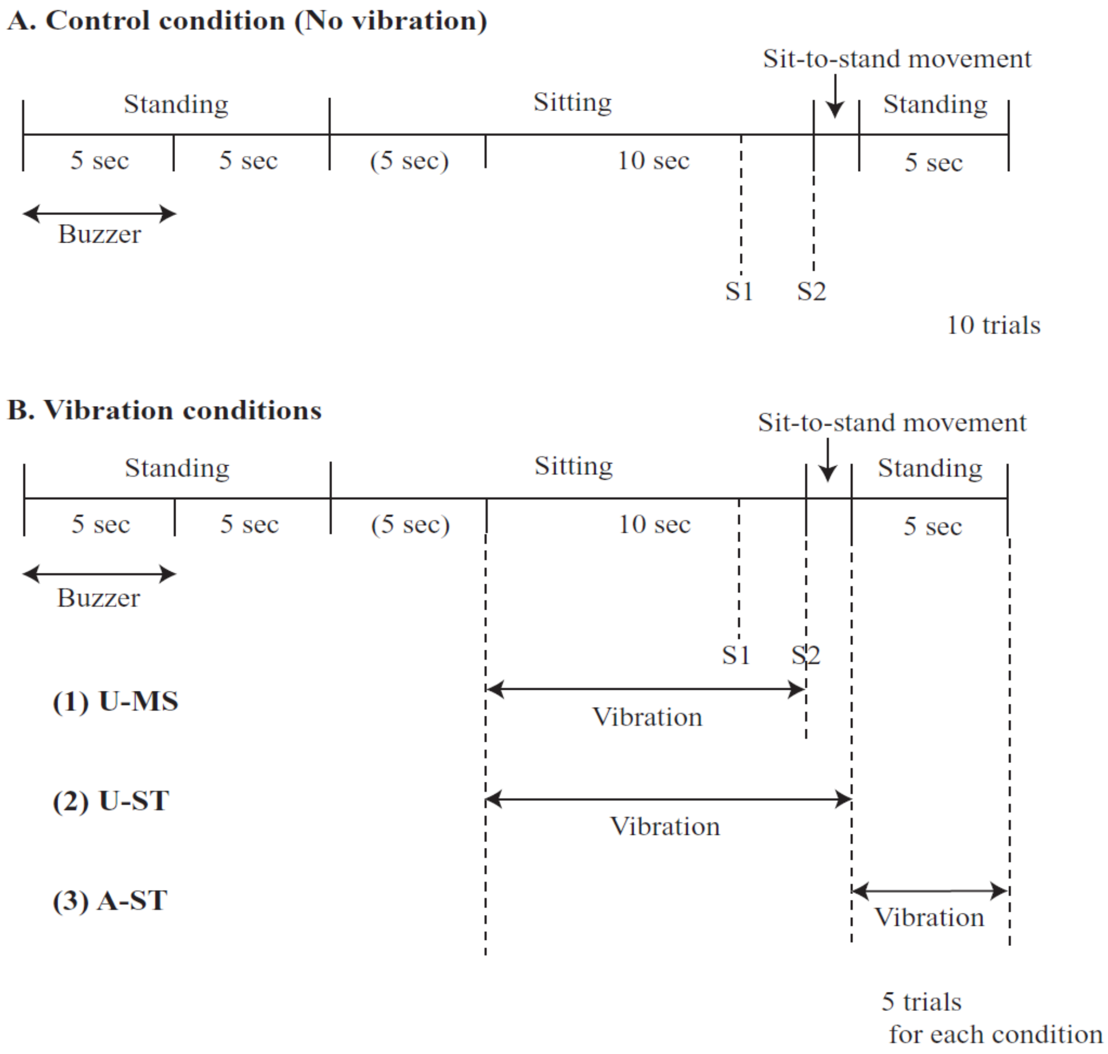

A. Control condition (No vibration)
Sit-to-stand movement
Standing
Sitting
Standing
5 sec
5 sec
(5 sec)
10 sec
5 sec
Buzzer
S1
S2
10 trials
B. Vibration conditions
Sit-to-stand movement
Standing
Sitting
Standing
5 sec
5 sec
(5 sec)
10 sec
5 sec
Buzzer
S1
S2
(1) U-MS
Vibration
(2) U-ST
Vibration
(3) A-ST
Vibration
5 trials
for each condition

Fig. 2

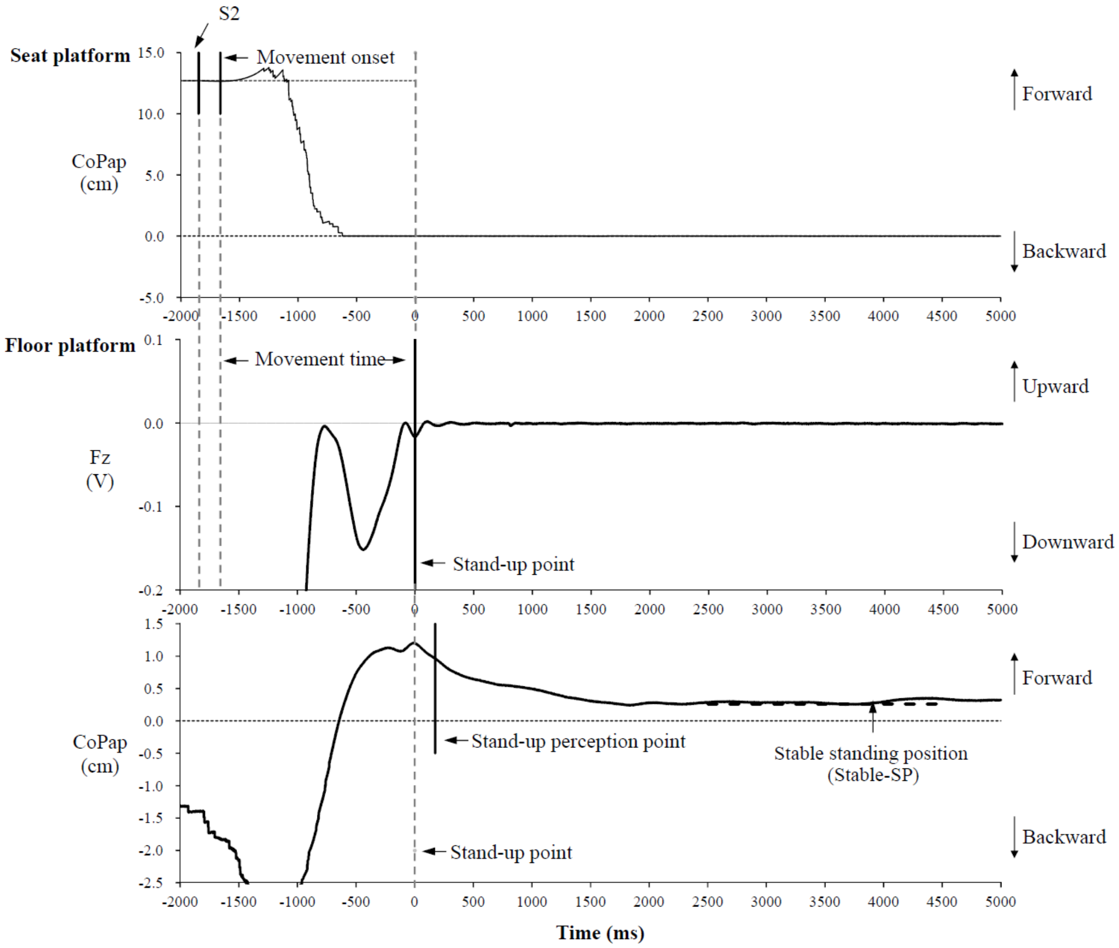

S2
Seat platform
Movement onset
Forward
CoPap (cm)
Backward
Floor platform
Movement time
Upward
Fz (V)
Downward
Stand-up point
Forward
Stand-up perception point
Stable standing position (Stable-SP)
CoPap (cm)
Backward
Stand-up point
Time (ms)

Fig. 3

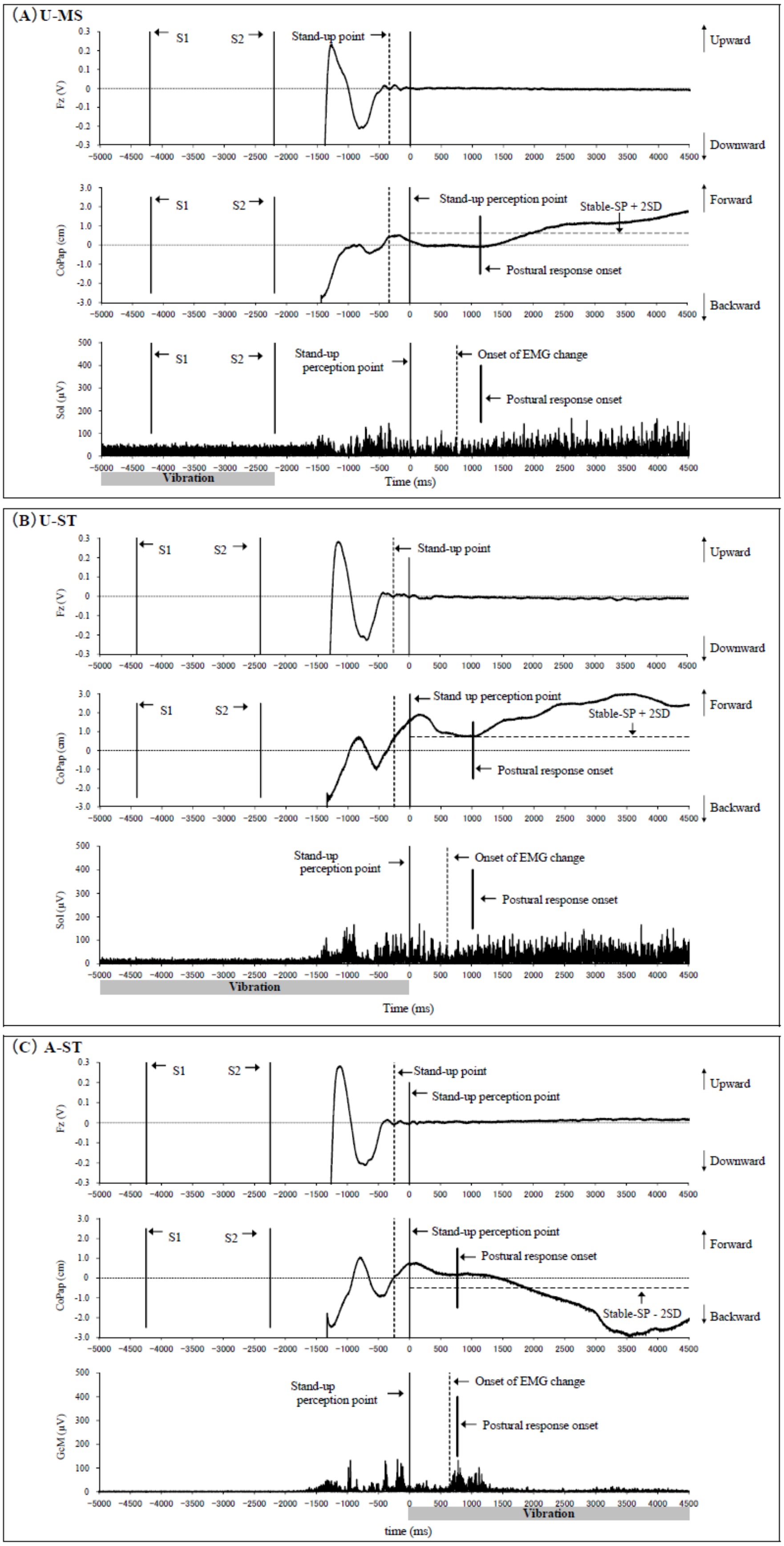
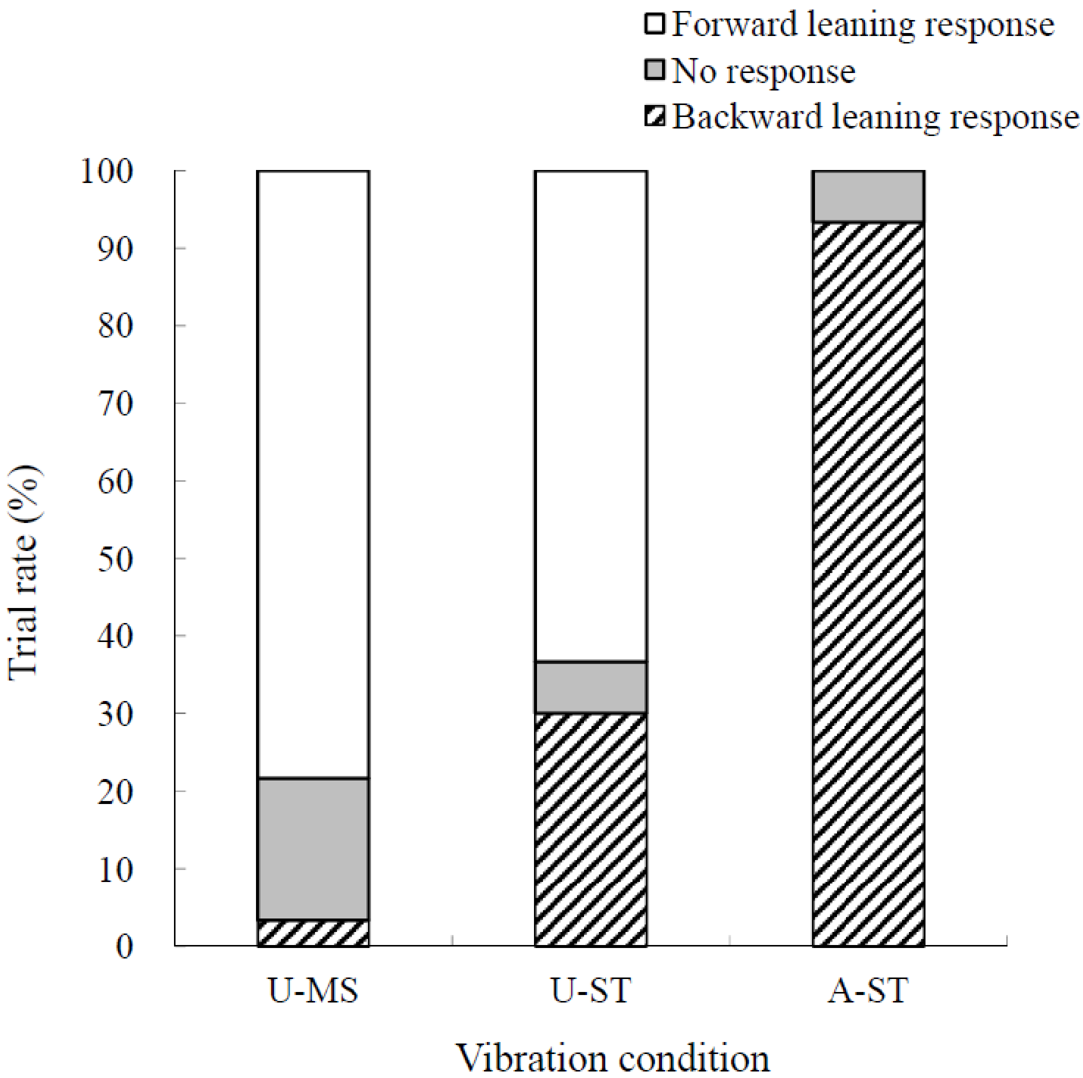

(A) U-MS
S1
S2
Stand-up point
Upward
Downward
Fz (V)
Stand-up perception point
Stable-SP + 2SD
Forward
Backward
CoPap (cm)
Postural response onset
Stand-up perception point
Onset of EMG change
Postural response onset
Sol (μV)
Vibration
Time (ms)
(B) U-ST
S1
S2
Stand-up point
Upward
Downward
Fz (V)
Stand up perception point
Stable-SP + 2SD
Forward
Backward
CoPap (cm)
Postural response onset
Stand-up perception point
Onset of EMG change
Postural response onset
Sol (μV)
Vibration
Time (ms)
(C) A-ST
S1
S2
Stand-up point
Stand-up perception point
Upward
Downward
Fz (V)
Stand-up perception point
Postural response onset
Stable-SP - 2SD
Forward
Backward
CoPap (cm)
Stand-up perception point
Onset of EMG change
Postural response onset
GcM (μV)
Vibration
time (ms)

Fig. 4



Forward leaning response
No response
Backward leaning response
100
90
80
70
60
50
40
30
20
10
0
Trial rate (%)
U-MS
U-ST
A-ST
Vibration condition

Fig. 5

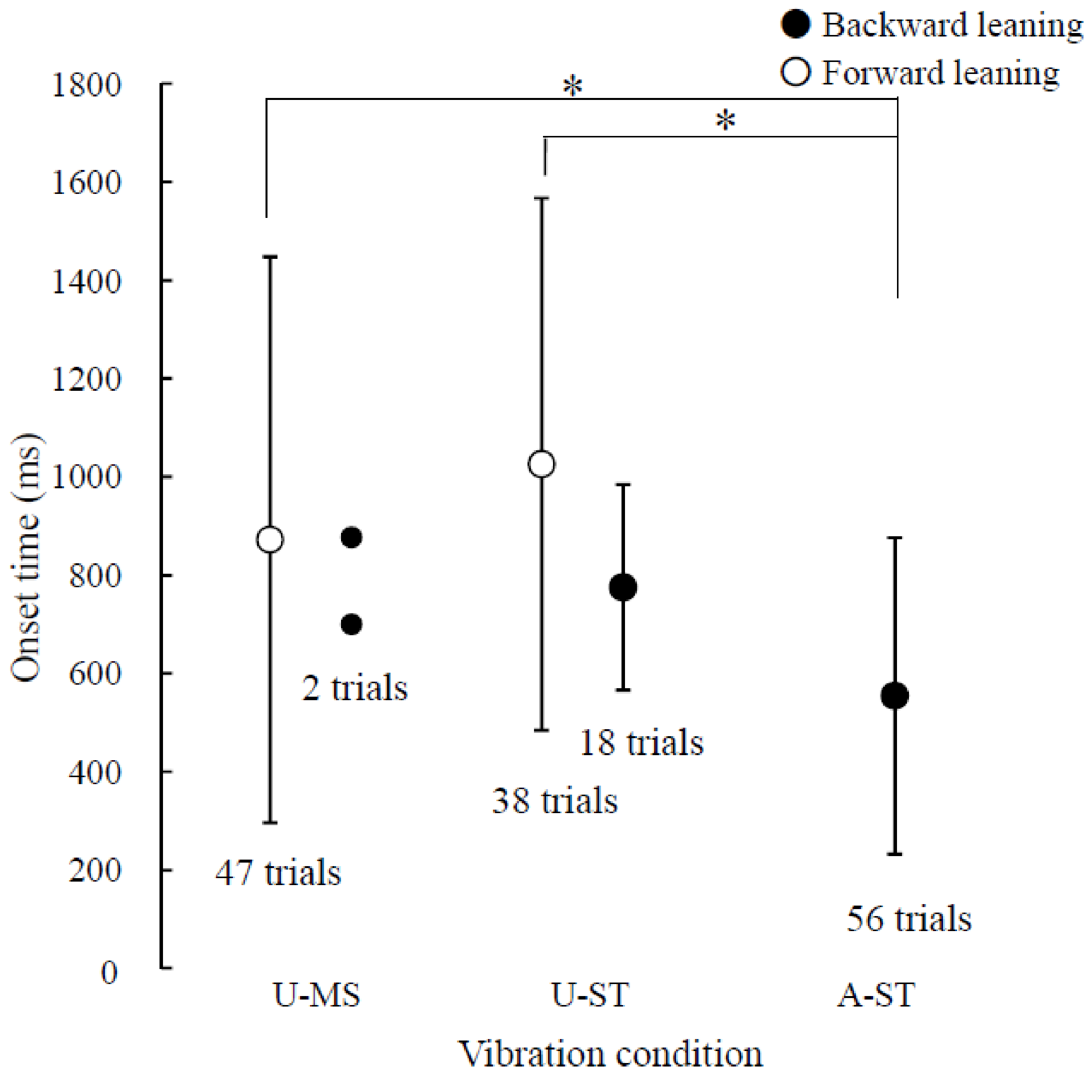

Backward leaning
Forward leaning
*
*
1800
1600
1400
1200
1000
800
600
400
200
0
Onset time (ms)
2 trials
47 trials
18 trials
38 trials
56 trials
U-MS
U-ST
A-ST
Vibration condition

Fig. 6

Table. 1

Postural response																		
	U-MS						U-ST						A-ST					
Trial number	1	2	3	4	5	Total	1	2	3	4	5	Total	1	2	3	4	5	Total
Backward leaning response	1	1	0	0	0	2	5	4	3	3	3	18	11	10	11	12	12	56
No response	2	1	4	2	2	11	1	1	0	1	1	4	1	2	1	0	0	4
Forward leaning response	9	10	8	10	10	47	6	7	9	8	8	38	0	0	0	0	0	0