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Postural sway during quiet standing is related to physiological tremor and muscle volume in young and elderly adults

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ABSTRACT

To examine the age-related deterioration in postural control, we investigated the association between postural sway during quiet standing and either amplitude of physiological tremor or muscle volume of the plantar flexors in 20 young and 20 elderly adults. They maintained a quiet standing position on a force platform for 60 s with their eyes open or closed. During quiet standing, physiological tremors detected using a piezoresistive accelerometer were recorded from the soleus muscle, and the center of pressure (COP) displacement and body acceleration in the antero-posterior direction were calculated using the ground reaction forces as an assessment of postural sway. Muscle volume was predicted from muscle thickness by an ultrasonographic image. The physiological tremor of the soleus muscle during quiet standing was significantly greater in elderly than in young adults, and a positive association between physiological tremor and the amplitude of postural sway was found for young and elderly adults combined. Furthermore, physiological tremor was positively correlated with the high-frequency component of COP sway during quiet standing. A significantly negative relation between the muscle volume of the plantar flexors and postural sway was found in both age groups. These results suggest that physiological tremor reflects high-frequency fluctuations in postural sway during quiet standing in young and elderly adults, and age-related increases in the postural sway amplitude in the antero-posterior direction may be related to a decrease in muscle volume of the plantar flexors for maintaining an upright posture.

1. Introduction

Age-related deterioration in postural control has been intensively investigated and well documented. Postural sway during quiet standing, frequently assessed using center of pressure (COP), is considered to be an effective measure to examine postural stability in the process of aging [1,2]. Numerous papers have reported that postural sway, especially fast components of postural sway such as the velocity of COP (e.g., [1,3]) and whole body acceleration [3] is larger in the elderly than in the young (e.g., [1,3]). However, its mechanism has remained an open question.

During quiet standing, the plantar flexors are key agonist muscles, because the ankle torque controls the center of mass (COM) behavior [4]; plantar flexor activity plays a key role in exerting ankle joint torque as the COM is in front of the ankle joint center; hence, the activity of the plantar flexors are correlated with spontaneous body sway [5]. Therefore, the neural regulation of the plantar flexor muscles is essential in the control of postural sway.

In terms of the activity of plantar flexor muscles during quiet standing, it has been found that the motor unit synchronization recurring at around 10 Hz is remarkable in the soleus (SOL) muscle of healthy subjects [6]. The recurring muscle activity generates a physical oscillation in the muscle that can be measured by mechanomyography [7]. This physical oscillation of the SOL during quiet standing is considered to be the same phenomenon as 'physiological tremor' [8]. It has been demonstrated that physiological tremor can result in force fluctuations in isometric contraction of the lower limb [9]. Indeed, during quiet standing, physiological tremor produces fluctuations in the force exerted by the foot [6].

It has been frequently reported that physiological tremor increases with aging [10]. Therefore, the reported evidence that both physiological tremor and postural sway during quiet standing increase with aging leads us to hypothesize that the increased physiological tremor in the elderly may cause larger postural sway, especially in fast components, during quiet standing compared to

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the young. Thus, the first purpose of this study was to test this hypothesis by investigating the association between the amount of physiological tremor and postural sway during quiet standing in the young and elderly.

Although neural regulation of the plantar flexor muscles is essential in the control of postural sway as mentioned above, the muscle properties, such as muscle volume and strength, around the ankle joint can also affect postural stability as the muscle is the effector of the neural command. Since age-related changes in muscle properties, such as muscle volume, are known to occur [11], it is very likely that the age-related postural instability is caused by the age-related deterioration in muscle properties. Studies have shown that muscle strength is associated with the incidence of falls [12,13], and that the muscle strength of the plantar flexors is correlated with the limit of stability in elderly people [14]. These findings suggest that maximum muscle strength can be closely related to dynamic balance measures such as the recovery of fall incidents and the limit of stability. However, the relationship between age-related deterioration of postural stability during quiet standing and decrement of muscle volume due to aging has not been explored at all. Since muscle volume is suggested to closely relate to muscle stiffness [15] and muscle stiffness plays a critical role in controlling quiet standing posture [16,17], age-related decrease in muscle volume of the prime mover for maintaining an erect posture in quiet stance can be more directly related to postural instability in the elderly than its strength. Therefore, the second purpose of the present study was to test this hypothesis by examining the association between the muscle volume of the plantar flexors and postural sway during quiet standing in both the young and elderly.

This study aimed to investigate the conceivable neural and anatomical independent factors of age-related postural instability in the elderly. The correlation between each factor and postural sway was examined in both the young and elderly.

2. Methods

2.1. Subjects

Twenty young men (range: 23–35 years) and 20 elderly men (range: 65–75 years) volunteered for this experiment. They gave their written informed consent for the study after receiving a detailed explanation of the purposes, potential benefits, and risks associated with participation in the study. All subjects were healthy and had no history of any neurological disorders, and their vision was normal or adequately corrected. All procedures used in this study were in accordance with the *Declaration of Helsinki* and were approved by the Committee for Human Experimentation at the Department of Life Sciences, The University of Tokyo.

2.2. Experimental protocol and measurement

The basic procedure for setup and measurement of postural sway during quiet standing has been described in our previous studies [1,5,18]. The subjects were required to maintain a quiet stance barefoot on a force platform (Type 9281B, Kistler, Zürich, Switzerland) with their eyes open (EO) or closed (EC) and with a distance of 15 cm between their heels, for approximately 70 s. The subjects held their arms by their sides. During each task, the foot center of pressure (COP) position and horizontal ground reaction force were measured. Body acceleration was calculated using the horizontal ground reaction force (ACC_{body}) [3]. Based on the dynamics of human quiet stance, the human body was approximated as a single joint inverted pendulum that rotates about the ankle joint [5]. Biomechanical study has indicated that anterior–posterior balance is predominantly under ankle control, whereas medial–lateral balance is under hip control [19]. Because the muscle activity of the plantar flexors as a main working muscle group contributes principally to the stabilization of the body in anterior–posterior direction [5,20], we focused only on the anterior–posterior direction of sway in this study. Three trials were conducted for each eye condition, and sufficient resting time was allowed between the trials. The order of the trials was randomized.

To assess the tremor of the SOL muscle during quiet standing, the acceleration detected using a uniaxial piezoresistive accelerometer (ASV-2GA, Kyowa, Tokyo, Japan) was recorded from the muscle belly of the right SOL muscle (ACC_{SOL}). The accelerometer had a flat frequency response from DC to 150 Hz, and its physical dimensions were 22 mm × 22 mm for the base, 11 mm in height, and 13 g in mass. A detailed account of the measurement method has been published elsewhere [7].

All electric signals were stored with a sample frequency of 1 kHz by a 16-bit analog-to-digital converter (PowerLab/16SP, ADInstrument, Sydney, Australia) and stored on the hard disk of a personal computer for later analyses.

2.3. Data analysis

For all recorded signals, data for a 60-s period in the middle portion of the collected data (~70 s) were selected for analysis of individual trials. Before calculations were performed, COP and ACC_{body} were low-pass filtered with a cutoff frequency of 15 Hz by a Butterworth filter [20]. The ACC_{SOL} was digitally filtered at a 5-Hz high-pass cutoff frequency by a Butterworth filter to remove movement artifacts induced by body sway during quiet standing [7].

To examine the contribution of postural feedback control, comprising integrated information from the vestibular, visual, and somatosensory systems [21], we analyzed the power spectral density of the COP sway. The 60-s data without low-pass filtering were first divided into seven segments that were 8192 points long (8.192 s). Almost half of the selected 8.192-s segments overlapped with the adjacent segments. A 13-bit fast-Fourier transform algorithm was then applied to these segments to yield the segments' power spectral density (cm^2/Hz). Consequently, the frequency resolution of the power spectral density was 0.122 Hz. An ensemble-averaged auto-power spectral density across these segments was calculated as the power spectral density of the COP sway. The power spectral density of COP sway greater than DC and less than 1 Hz was integrated and defined as the low-frequency component (LF) of the COP sway [20], while the power spectral density of the COP sway from 1 to 10 Hz was integrated and defined as the high-frequency component (HF) of the COP sway [20]. It has been reported that the LF and HF components of postural sway reflect the different postural control system: LF has shown to reflect the sensitivity of vestibular and visual information [22], and HF has been reported to depend on somatosensory inputs including proprioception [23].

The power spectral density of the high-pass filtered ACC_{SOL} was calculated to extract the tremor component. The procedure was the same as that for calculating the power spectral density of COP sway. Briefly, the data for 60 s were divided into 13 subsets with a length of 8192 data points (8.192 s). A 13-bit fast-Fourier transform algorithm was then applied to generate a periodogram for each subset. An ensemble-average auto-power spectral density was calculated across these segments. Acceleration or fluctuation in motor output around 8–12 Hz, referred to as "physiological tremor", has been observed during quiet standing [7] and during low-level sustained contraction [9]. Therefore, the power-spectrum density of ACC_{SOL} from 8 to 12 Hz was integrated and defined as the tremor observed during quiet standing [7].

To assess the magnitude of postural sway during quiet stance, the mean velocity of COP sway (COP path-length per calculated time) in the anteroposterior direction was calculated [1,20], as this is the most sensitive measure for postural control assessment related to regulatory balancing activity [2]. We also calculated the standard deviation (SD) of ACC_{body}, because the ACC_{body} is proportional to the distance between COP and the vertical projection of the COM during quiet standing [3]. The variability of this distance has been accepted as a good assessment of spontaneous body sway during quiet standing [24].

The muscle volume of the plantar flexors as the main working muscle group for maintaining erect posture was estimated by an established methodology for predicting the muscle volume of plantar flexors from ultrasonography [25]. A single cross-sectional image of the posterior surface at 30% of the lower leg length (the distance from the articular cleft between the femur and tibia condyles to the lateral malleolus) on the right limb was obtained using a B-mode ultrasonographic apparatus (SSD-900, Aloka, Tokyo, Japan). The estimated muscle volume was predicted by multi-regression equations using muscle thickness obtained from the ultrasonographic image and lower limb length. The muscle volume was normalized by body weight (BW) because BW affects muscle volume size, and the BW was significantly different between young (mean ± SD: 69.3 ± 8.3 kg) and elderly adults (61.1 ± 7.9 kg).

2.4. Statistical analyses

The mean velocity of COP, SD of ACC_{body}, tremor, and each frequency component of COP sway were compared with a two-way repeated measure ANOVA (two age groups, and two eye conditions). The estimated muscle volume was compared with a one-way repeated measure ANOVA (two age groups). An alpha level of 0.05 was chosen for all initial statistical comparisons, with a Tukey post hoc comparison performed when necessary. Correlation analysis was also performed between the variables with combining young and elderly subjects to investigate the effect of tremor and muscle volume on a wider range of postural stability. Data are given as means ± SD in the text and tables, and as means ± SE in the figures.

3. Results

Typical time series of the COP, ACC_{body}, and ACC_{SOL} during quiet standing for 60 s in one young and elderly adult are shown in Fig. 1.

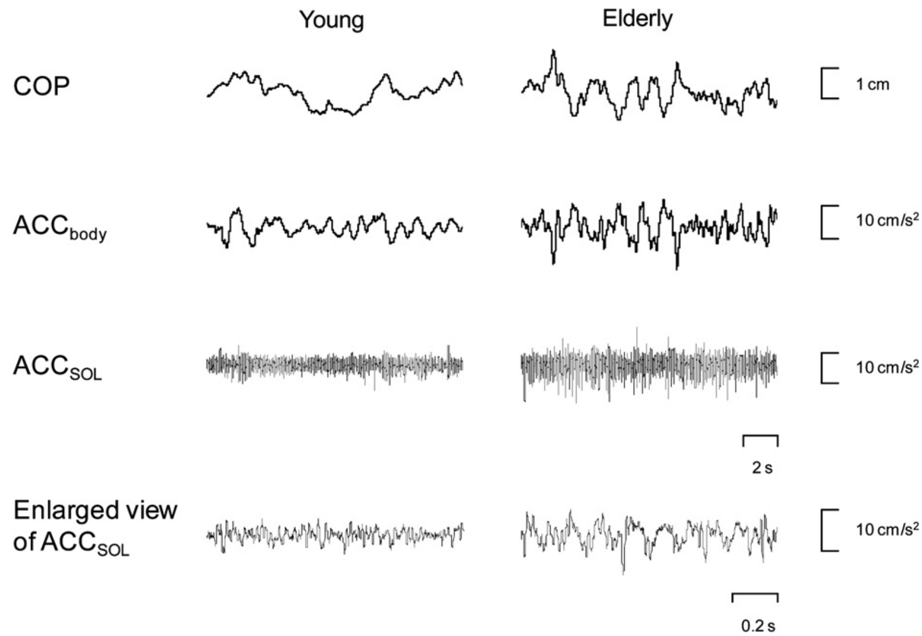

Fig. 1. Representative example of time series of center of pressure (COP), body acceleration (ACC_{body}), and acceleration obtained from soleus muscle (ACC_{SOL}) for a single trial during quiet standing in young (left panels) and elderly subjects (right panels). Note that only 15 s of data out of the analyzed 60 s were presented to isolate the signal features. The bottom rows of both panels show an enlarged view with an extended time scale (1 s) of the ACC_{SOL} in the second-from-the-bottom row for visual purposes. The time series of ACC_{SOL} was passed through a high-pass filter of 5 Hz.

It can be seen that the COP and ACC_{body} fluctuate while ACC_{SOL} exhibits tonic activity in a global view. Comparing the data of young and elderly subjects, it seems likely that the trajectory of COP and ACC_{body} showed more complex fluctuation in the elderly than in the young-adult subjects. Only 1-s windows are presented in the bottom traces for an enlarged view of ACC_{SOL}. The amplitude appeared to be larger in the elderly than the young adults, and it can be seen that the periodic activity occurs with an interval of about 0.1 s in the elderly adults. Furthermore, ACC_{SOL} with extended scale in the young adults appears not to be cyclic.

In the group data, the effect of age was significant in each ANOVA test for the mean velocity of COP, SD of ACC_{body} and tremor component of SOL calculated from ACC_{SOL} ($P < 0.05$, Fig. 2), while the effect of eye conditions was not significant. The postural sway measures in EC were approximately 1.3-times as large as that in EO for the combined data of both age groups (mean velocity of COP: 1.28 ± 0.24 times, ACC_{body}: 1.33 ± 0.32 times). There was no significant interaction between these two main factors. In contrast, the muscle volume of plantar flexors in the elderly was significantly smaller than that in young adults ($P < 0.05$, Fig. 2). The main effect of age was not significant for the LF of COP, while the HF of COP in the elderly was significantly larger than that in young adults ($P < 0.05$, Fig. 2).

The normalized muscle volume and tremor component were plotted against the mean velocity of COP sway (Fig. 3A) and the SD of ACC_{body} (Fig. 3B). A significant negative correlation was obtained between the normalized muscle volume of plantar flexors and the mean velocity of COP sway in EO ($r = -0.399$, $P < 0.05$) and EC ($r = -0.345$, $P < 0.05$) for the combined data of both age groups. Likewise, a significant correlation was found between the tremor component and the mean velocity of COP sway in EO ($r = 0.549$, $P < 0.01$) and EC ($r = 0.627$, $P < 0.01$) for the combined data of both age groups (Fig. 3A).

For the fluctuations in ACC_{body}, there were significant correlations between the SD of ACC_{body} and either normalized muscle volume (EO: $r = -0.326$, $P < 0.05$, EC: $r = -0.406$, $P < 0.01$) or the tremor component (EO: $r = 0.435$, $P < 0.01$, EC: $r = 0.416$, $P < 0.05$) in both eye conditions (Fig. 3B).

To examine whether the tremor component was related to the frequency feature of COP sway, the correlation between the tremor component and LF and HF of COP was assessed in both age groups combined (Fig. 4). A significant positive correlation was found between tremor and HF of COP in both eye conditions (EO: $r = 0.455$, $P < 0.01$, EC: $r = 0.444$, $P < 0.01$). In contrast, there was no significant correlation between tremor and LF of COP in EO and EC.

The LF and HF of COP were plotted against the normalized muscle volume (Fig. 5). A significant negative correlation was obtained between the normalized muscle volume and HF of COP in both eye condition (EO: $r = -0.322$, $P < 0.05$, EC: $r = -0.385$, $P < 0.05$). On the other hand, there was no significant correlation between muscle volume and LF of COP in EO and EC.

4. Discussion

The present study compared postural sway measures, such as the COP velocity and ACC_{body}, during quiet standing, physiological tremor, and muscle volume of the plantar flexors between young and elderly adults, and the correlation between postural sway and either physiological tremor of SOL or muscle volume of the plantar flexors. The main findings were that: (1) the physiological tremor of the SOL during quiet standing was greater in elderly than young adults, while the muscle volume of plantar flexors was smaller in the elderly than the young, (2) the physiological tremor component was positively correlated to postural sway (mean velocity of COP and ACC_{body}) for young and elderly adults combined, while muscle volume was negatively correlated, and (3) physiological tremor positively correlated with the HF component of COP, while muscle volume negatively did.

4.1. Association between physiological tremor and postural sway in young and elderly adults

The present study demonstrated that the amplitude of physiological tremor observed in the SOL during quiet standing is greater in the elderly than in young adults. To our knowledge, this is the first paper indicating an age-related difference in

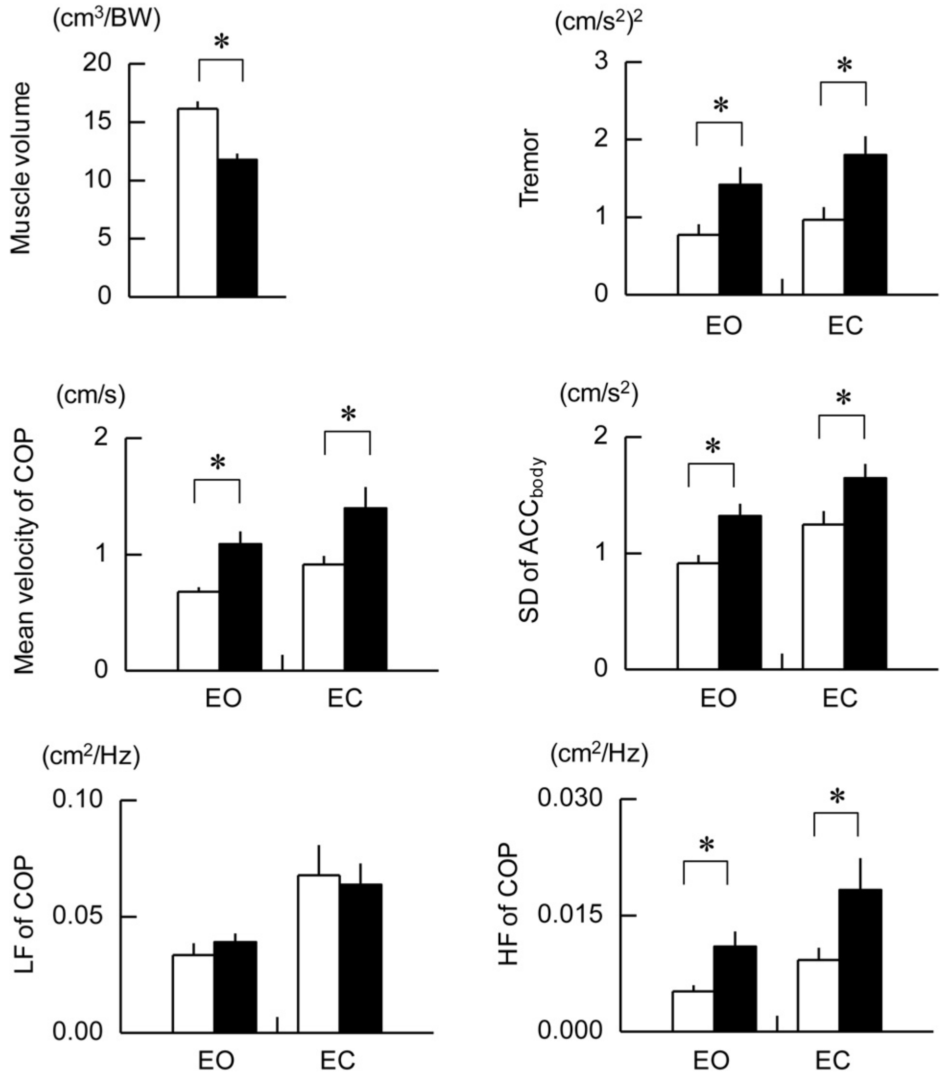

Fig. 2. Group-averaged tremor component of SOL, muscle volume of plantar flexor muscle group, mean velocity of COP, standard deviation (SD) of ACC_{body}, and low-frequency (LF) and high-frequency (HF) components of COP sway during quiet standing with eyes open (EO) and closed (EC). Open and filled bars indicate young and elderly adults, respectively. *, Significant difference between subject groups ($P < 0.05$).

physiological tremor during bipedal standing between young and elderly adults. Many researchers have suggested that physiological tremor is partly due to rhythmic modulation of the activity of several motor units caused by a servo-loop oscillation in the stretch reflex arc [8]. An increase in physiological tremor with age has been well documented in hand muscles [10]. The reported increase in tremor amplitude observed in elderly adults is believed to derive from a decline in the functional capacity of an aging neuromuscular system [26], and there is no significant effect of aging on its frequency [26]. Therefore, the physiological tremor during quiet standing agrees with the previous observations obtained in finger joints in isometric tasks.

In the present study, a significantly positive association was found between physiological tremor of SOL and fast postural sway measures such as COP velocity and ACC_{body} during quiet standing for young and elderly adults combined (Fig. 3). Further, the physiological tremor correlated with HF of COP while it did not correlate with LF (Fig. 4). As the COP is proportional to the ankle torque [5], the correlation between physiological tremor and HF of COP can be mainly accounted for by a mechanical consequence, i.e., the physiological tremor showed up as a small ankle torque fluctuation. This agrees with Mori's study [6] showing that an 8 Hz motor unit activity is synchronized with a small force fluctuation at the foot. However, the correlations between physiological tremor and COP velocity or ACC_{body} imply that such small force fluctuation may induce the fast postural sway of COM. The age-related increment in postural sway has been frequently shown using COP velocity, while the COP amplitude or the COM amplitude are not prominently different [2,5]. Therefore, the correlation between the physiological tremor magnitude and the fast component of COP may suggest that the physiological tremor causes the fast component of COP fluctuation and hence the age-related deterioration of postural control. Studies that have demonstrated that both physiological tremor [8] and the fast component of COP during quiet standing [20,21] are regulated through the proprioceptive system may support this as well. However, as the correlation does not necessarily indicate a causal relation, further physiological studies are required.

4.2. Association between muscle volume and postural sway in young and elderly adults

The present study demonstrated that the normalized muscle volume of the plantar flexors is smaller in the elderly than in young

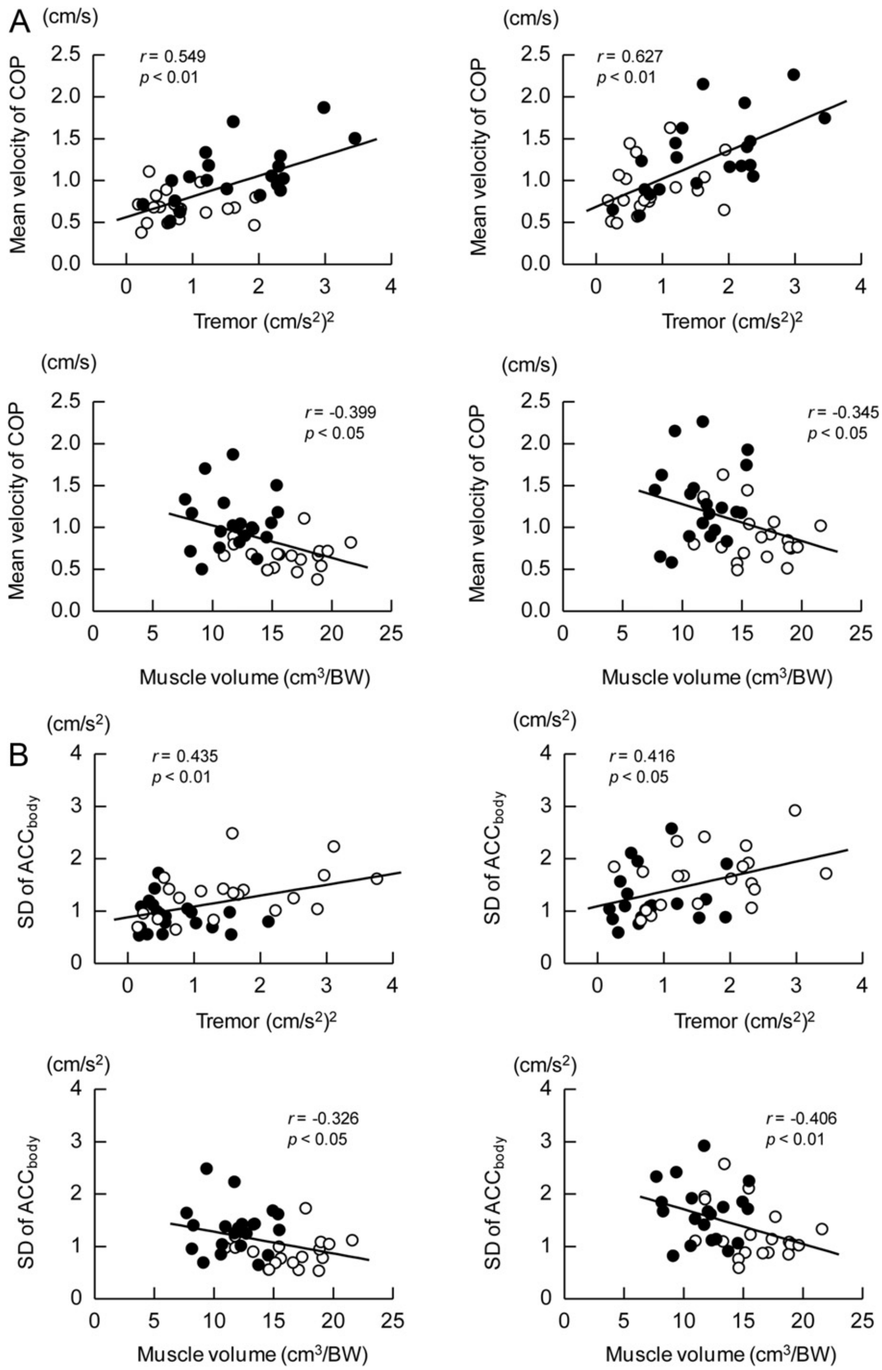

Fig. 3. A. Scatter plots of mean velocity of COP as a function of muscle volume and tremor component during quiet standing with EO (left panels) and EC (right panels). B. Scatter plots of SD of ACC_{body} as a function of muscle volume and tremor component during quiet standing with EO (left panels) and EC (right panels). Open and filled symbols indicate young and elderly adults, respectively. Superimposed lines indicate the linear regression lines with statistical significance ($n = 40$, $P < 0.05$) for young and elderly adults combined.

adults (Fig. 2). The present study also demonstrated that the normalized muscle volume of the plantar flexors is negatively correlated with fast components of postural sway (Fig. 3).

It has been shown that the muscle maximum strength is related to falls [12,13] and limit of stability [14] in the elderly, which are associated with the dynamic stability. However, during quiet standing, the muscle activity is far smaller than the maximum, i.e., the activity of the planter flexors is at about 5–20% of maximum [1,20]. Therefore, maximum strength may not directly relate to postural stability during quiet standing. Instead, the muscle volume may be more directly related to the postural stability. First, since muscle volume is suggested to closely relate to muscle stiffness [15] and muscle stiffness plays a critical role in controlling quiet standing posture [16,17], muscle volume can be a critical factor in controlling balance during quiet standing. Secondly, it has been shown that the ability of a force-matching task is dependent on the magnitude of the muscle volume in the plantar flexors and knee extensors [27]. Postural regulation is a sort of force-matching task [1], as the ankle torque must be matched with the gravity-toppling torque and the difference between the ankle torque and gravity-toppling torque is proportional to the body acceleration. Therefore, the negative correlation between the muscle volume

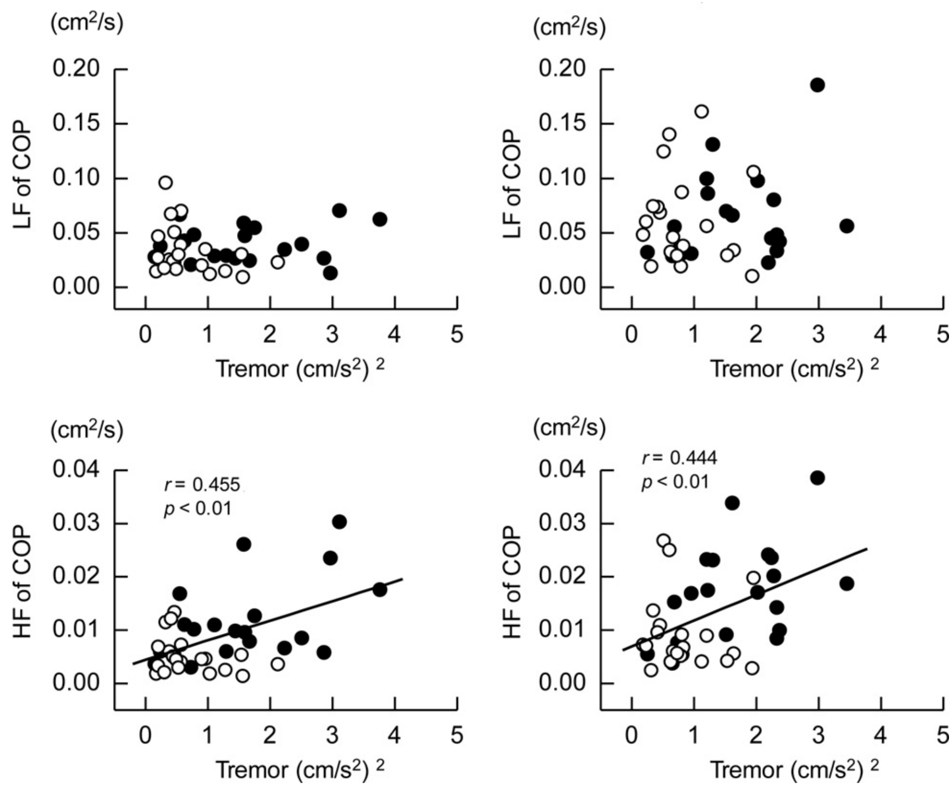

Fig. 4. Scatter plots of LF (upper panels) and HF (lower panels) of COP as functions of the tremor component during quiet standing with EO (left panels) and EC (right panels). Open and filled symbols indicate young and elderly adults, respectively. Superimposed lines indicate the linear regression lines with statistical significance ($n = 40$, $P < 0.05$) for young and elderly adults combined.

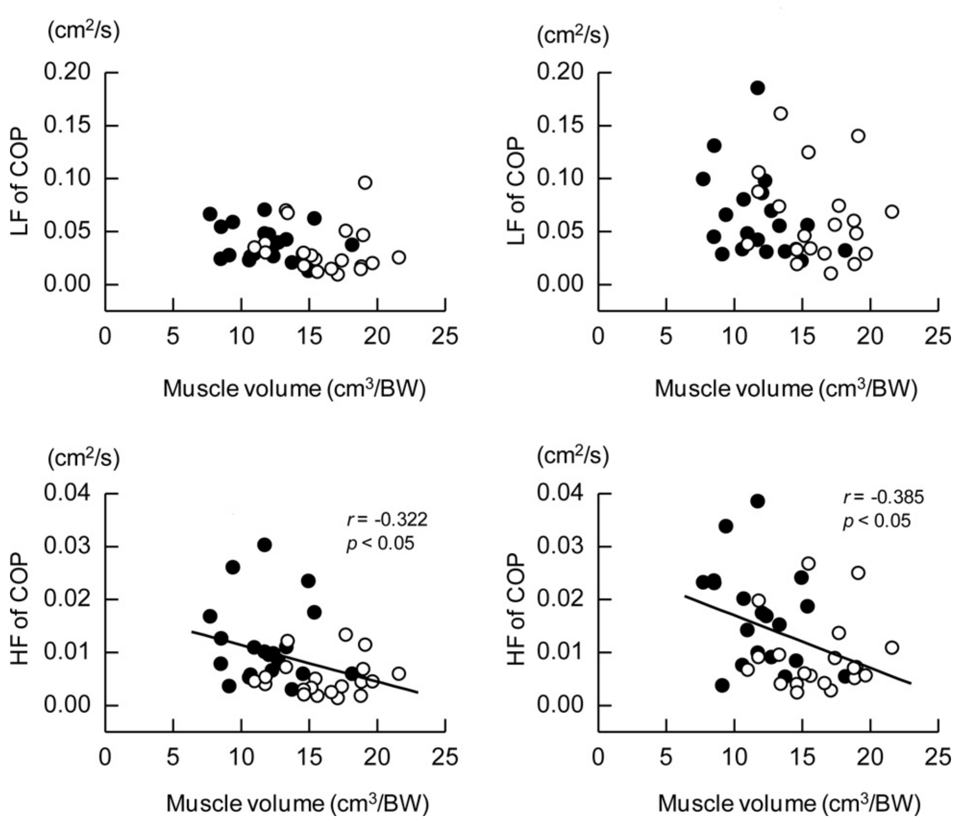

Fig. 5. Scatter plots of LF (upper panels) and HF (lower panels) of COP as functions of normalized muscle volume of plantar flexors with EO (left panels) and EC (right panels). Open and filled symbols indicate young and elderly adults, respectively. Superimposed lines indicate the linear regression lines with statistical significance ($n = 40$, $P < 0.05$) for young and elderly adults combined.

and the postural sway may suggest that the diminished ability of force-matching due to reduction in muscle volume causes the postural instability. Therefore, the muscle volume may be the more relevant factor in relation to postural stability during quiet standing.

In the present study, the muscle volume was negatively correlated with the HF (from 1 to 10 Hz) component, but not the LF ($\leq$1 Hz) component of COP sway (Fig. 5). In a bedrest study, we indicated that the reduced ability in controlling force during isometric plantar flexion and knee extension was correlated to a decrease in muscle volume of the lower limbs due to inactivity [27]. Furthermore, our subsequent study demonstrated that this increase in force fluctuations due to bedrest was mainly accounted for by an increase of force fluctuations at the frequency range from 1 to $\sim$10 Hz during the force-matching task in plantar flexion [28]. These previous studies imply that the magnitude of muscle volume in the lower limbs is related to the higher-frequency range of force fluctuations during force-matching tasks. Because the force level and force fluctuation during quiet standing were close to those during a force-matching task of plantar flexors [1], it is possible that the muscle volume is related not to the LF but to the HF component of COP sway during quiet standing. Therefore, it can be suggested that the muscle volume of the plantar flexors is a key factor for postural stability.

4.3. Effect of vision

Visual information has an important role in balance control by providing the nervous system with continuously updated information regarding the position and movements of body segments [29]. In elderly adults, it was reported that poor vision accompanied by a loss of balance increases the risk for falls [29]. In the present study, the postural sway tended to be greater in EC than in EO, however, there was no influence of visual information (i.e., EO and EC conditions) on the relation between postural sway and either physiological tremor or muscle volume. Therefore, poor vision for maintaining postural sway with advancing age did not result in the modulations of the relation between postural sway and either physiological tremor or muscle volume.

5. Conclusion

In the current study, we found that: (1) the physiological tremor of the SOL during quiet standing was greater in elderly than young adults, while the muscle volume of the plantar flexors was smaller in the elderly than the young, (2) the physiological tremor component was positively correlated to postural sway measures such as COP velocity and ACC_{body} for young and elderly adults combined, while muscle volume was negatively correlated, and (3) physiological tremor positively correlated with the HF component of COP, while muscle volume negatively did. These findings suggest that physiological tremor of the SOL may cause the fast components of postural sway during quiet standing in young and elderly adults, and that age-related increases in the postural sway in antero-posterior direction amplitude may be related to decreases in muscle volume of the main working muscles for maintaining an upright posture. Further physiological studies are required to confirm these conclusions.

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Conflict of interest

There is no conflict of interest.

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