Title: Smaller Sway Size during Quiet Standing is Associated with Longer Preceding Time of Motor Command to Body Sway

Authors: Kei Masani [1), 2)], Albert H. Vette [1),2)], Masaki O. Abe [3)],
Kimitaka Nakazawa [4)], Milos R. Popovic [1),2)]

[1] Rehabilitation Engineering Laboratory,
Institute of Biomaterials and Biomedical Engineering, University of Toronto
164 College Street, Toronto, Ontario M5S 3G9, Canada
[2] Rehabilitation Engineering Laboratory,
Lyndhurst Centre, Toronto Rehabilitation Institute
520 Sutherland Drive, Toronto, Ontario M4G 3V9, Canada
[3] Action Lab, Department of Biology, Northeastern University
134 Mugar Life Science Building, 360 Huntington Avenue,
Boston, Massachusetts 02115, USA
[4] Department of Life Sciences,
Graduate School of Arts and Sciences, The University of Tokyo,
3-8-1 Komaba, Meguro, Tokyo 153-8902, Japan

Corresponding Author:
Kei Masani PhD
Rehabilitation Engineering Laboratory, Lyndhurst Centre,
Toronto Rehabilitation Institute
520 Sutherland Drive, Toronto, ON, M4G 3V9, Canada
Phone: +1-416-597-3422 ext 6098 / Fax: +1-416-425-9923
E-mail: k.masani@utoronto.ca

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Abstract

In previous studies, it was found using cross-correlation analysis that the modulation of the motor command to the calf muscles largely precedes body sway during quiet standing. The purpose of this study was to investigate whether this preceding time is correlated with an improved stabilization of the body. 26 young and 23 elderly healthy subjects were asked to stand quietly. Body sway was measured using a laser displacement sensor, and the electromyogram of the right soleus was measured as a representative of the motor command. The correlation and time shift between motor command and body sway were estimated by means of cross-correlation analysis. We found that sway size was correlated with the identified time shift, i.e., that a smaller sway size was associated with a longer preceding time. The obtained results suggest that a control strategy generating a larger preceding time can stabilize the body more effectively. This result was found in both the young and elderly, suggesting that the particular control aspect associated with the time shift is a common feature in both age groups.

[176 words]

Introduction

The nature of the control mechanism responsible for ensuring stability during quiet standing has attracted the attention of many researchers. As the non-moving feet are the only contact with the external environment during quiet standing, the ankle joint is responsible for balancing the entire weight of the body. Thus, one of the major problems to be solved to understand the control mechanism of balance during quiet standing is how the ankle torque is modulated to stabilize the body, and in particular its center of mass (COM). Furthermore, since the stable condition during quiet standing can be defined as the condition for which the COM fluctuation is small, it is beneficial to identify those control characteristics that can decrease COM sway.

Active control provided by the central nervous system (CNS) as well as passive mechanical structures contribute to the stabilization of the body during quiet standing [1-5]. The passive mechanical forces produced by muscles and surrounding tissues take part in the modulation of the ankle torque, but have been shown to be insufficient for body stabilization [6-8]. Since numerous studies have demonstrated that quiet stance posture can be perturbed by stimulating various sensory systems (e.g., [9-14]; for review: [15]), the CNS must modulate an additional active ankle torque component moment to moment.

Active control involves a delay in the neural feedback loop, which includes neural transmission delays from and to the CNS [16, 17]. Further, we demonstrated that the torque generation process in the ankle extensors, i.e., the process from the motor command arriving at the muscles to the torque generation, introduces a considerable delay during quiet standing [18]. Since these feedback delays have a destabilizing effect on the postural control system, a control strategy is required that can overcome the delays by issuing a motor command that precedes body sway.

Gatev et al. (1999) first found the preceding motor command in an ankle extensor during quiet standing using cross-correlation analysis. They reported that the rectified electromyogram (EMG) fluctuation of the lateral gastrocnemius muscle matches and precedes the fluctuation of COM: When the body moves forward/backward, the EMG increases/decreases in advance. They concluded from this result that the CNS must include a feed-forward control strategy to generate a motor command that precedes the body behavior. Also our team reported that the muscle activity of the soleus muscle precedes COM [3]. However, we demonstrated using simulation studies that the preceding nature of the motor command can be accomplished by a simple linear feedback controller with a large derivative gain in the neural controller [3, 19]. Thus, although the control strategy that is responsible for generating the preceding motor command is still under debate, strong experimental evidence exists that the motor command does precede the body behavior during quiet standing.

The control strategy that can generate such a preceding motor command must be beneficial in terms of overcoming the delay in the neural feedback loop. In other words, a control strategy that can generate a larger preceding motor command may be able to stabilize the body better. Thus, we hypothesized in the present study that the preceding time is correlated with postural stability, i.e., that a longer preceding time is related to an improved stabilization of the body during quiet standing. Further, as it has been suggested that postural control is affected by aging [15, 20], we also investigated a potential age-related difference in the preceding time and/or the relationship between the preceding time and postural stability during quiet standing.

Methods

26 healthy adults (13 female and 13 male; age 27.3±4.6 years; height 168±9 cm; weight 60.2±7.9 kg) and 23 elderly healthy adults (12 female and 11 male; age 66.2±5.0 years; height 157±7 cm; weight 58.2±8.3 kg) participated in this study. They had no medical history or signs of neurological disorders. All subjects gave their written informed consent to participate in the study after having received a detailed explanation about the purposes, benefits, and risks associated with the execution of the study. The experimental procedures used in this study were approved by the local ethics committee.

Each subject stood quietly with bare feet, eyes open, and the arms hanging along the sides of the body for the duration of 90 s. The subject was instructed to stand relaxed and quietly and to refrain from any voluntary limb and head movements. Each subject completed five trials with sufficient resting time in between the trials. The horizontal position around the third lumbar vertebra (L3) measured with a high-accuracy laser displacement sensor (LK-2500, Keyence, Japan) was used as an approximation of the COM of the body. Note that, in this study, we focused only on the anteroposterior body sway, since body sway is more prominent in this direction compared to the mediolateral direction.

The ankle extensors are the prime movers in generating the active ankle torque, since they show continuous activity, whereas the ankle flexors are silent or only intermittently active. Among the ankle extensors, it has been reported that soleus activity during quiet standing is about 5 % and gastrocnemius activity about 1 % of their activity potential (Panzer et al., 1995). Additionally, the physiological cross-sectional area of soleus is twice as large as the total area of the medial and lateral gastrocnemius (Yamaguchi et al., 1990). Therefore, we assumed that, in standing, the soleus contribution to the generation of the ankle torque is much larger than the medial and lateral gastrocnemius contribution, even when the difference in fiber types among the two muscles is considered (Yamaguchi et al., 1990). Thus, we decided to use only soleus EMG in this study. The surface EMG of the right soleus muscle was acquired with a band-pass filter between 20 and 450 Hz (Bagnoli 8 EMG System, Delsys, U.S.A.). To confirm that the calf muscles are the dominant contributors to the ankle torque (no or only intermittent activity of the dorsiflexors), the activity of the tibialis anterior muscle was also recorded. After confirming that the activity of the tibialis anterior muscle was as small as that during the resting condition, we decided not to analyze the tibialis anterior recordings.

All data were sampled at 1 kHz and stored on a personal computer for subsequent analysis. Both the rectified EMG and kinematic time series (90 s each) were low-pass filtered using a fourth-order, zero phase-lag Butterworth filter. Since this study mainly investigates the concordance of low-frequency body movements with muscle activity [13], the cutoff frequency of the Butterworth filter was set to 4 Hz [3]. Note that the rectified and smoothed EMG was considered to represent the modulation of the motor command to the calf muscles during quiet stance (Masani et al. 2008). Finally, the processed time series were used in the cross-correlation analysis as described below.

The correlation coefficient (CC) and time shift (TS) were determined using the peak of the normalized cross-correlation function between the COM displacement and the motor command. The cross-correlation function ($R_{xy}(\tau)$) was defined as follows:

$$R_{xy}(\tau) = \frac{\overline{x(t+\tau)y(t)}}{\sqrt{\overline{x^2}}\sqrt{\overline{y^2}}}, \quad (1)$$

where x and y denote two target signals with zero means, τ denotes the time lag of y with respect to x, and the overbar denotes an average over time t. The fast Fourier transform (FFT) was used to calculate the cross-correlation function according to the procedure described by Bloomfield [21], and the FFT parameters were taken from Masani et al. (2003). First, the cross-power spectral density between $x(t)$ and $y(t)$ was calculated using a 2^{13}-point FFT with half-overlapping segments. Then, $\overline{x(t+\tau)y(t)}$ was obtained by applying the inverse FFT to this cross-power spectral density function. After calculating the cross-correlation function for the data of each trial, the ensemble-averaged cross-correlation function was identified (from five cross-correlation functions) as a representative of each subject's cross-correlation function.

The body sway size during quiet standing was assessed using the root mean square (RMS) of the COM displacement (COM_{RMS}) after eliminating its offset. Spearman's rank correlation coefficients were calculated between CC and COM_{RMS}, and between TS and COM_{RMS}.

Results

Fig. 1 shows an example of the experimental recordings (A) and the cross-correlation function (B). Note that only excerpts of the time series and cross-correlation function are shown to reveal the signal characteristics. Based on a simple visual inspection, it can be suggested that the fluctuations of the COM displacement and motor command closely resemble each other. Accordingly, the cross-correlation function revealed a clear peak by which CC and TS could be determined (Fig. 1B). The peak showed a positive value (positive CC value) indicating that, when the motor command increased (decreased), the

COM moved forward (backward). Furthermore, the peak was found at a negative time shift (negative TS value), which indicates that the muscle activity preceded the COM displacement. This positive peak at a negative time shift was a common feature for 47 out of 49 subjects. Two subjects exhibited a CC that was lower than 0.195 at which CC is statistically different from zero ($p < 0.05$, n = ∞). In particular, these subjects' values were CC = -0.08 and TS = 4.078 s (young, male), and CC = 0.113 and TS = 0.092 s (elderly, female). Due to the non-significance of the CC values, the data of these subjects were not included in the following analysis.

In Table 1, COM_{RMS}, CC, and TS are summarized for both age groups separately and combined. No significant differences were found between the age groups in any of the group mean values of COM_{RMS}, CC, and TS ($p > 0.05$, *t*-test). Fig. 2 shows the correlation between CC and COM_{SD} (A), and between TS and COM_{RMS} (B). In each plot and in each age group or both age groups combined, there is a tendency that CC increases and the absolute value of TS decreases with growing COM_{RMS}. The correlation coefficient between CC and COM_{RMS} revealed a significant correlation ($p < 0.001$, Fig. 2A) except for the young age group. The correlation coefficient between TS and COM_{RMS} indicated a significant correlation for each age group and both age groups combined ($p < 0.01$, Fig. 2B).

Discussion

We demonstrated that, for 47 out of 49 subjects, body sway size is highly correlated with CC and TS. When sway size was smaller (larger), CC was smaller (larger) and the absolute value of TS larger (smaller). The correlation with sway size was more significant for TS than for CC since the correlation with CC was not significant in the young group, whereas the correlation with TS was significant and very high in both groups.

The neural control mechanism in the CNS modulates the ankle torque with the support of the forces provided by the passive mechanical structures. The neural control strategy is one of the critical components affecting the ankle torque modulation and, hence, the balance performance as measured with sway size. As a consequence, the control strategy in the CNS should also affect body sway size, i.e., a more effective neural controller should reduce body sway size. Therefore, the result that TS is strongly correlated with body sway size indicates that a control strategy producing a longer preceding time of the motor command can stabilize the body more effectively.

Although the actual neural control system still remains unclear, the current result implies that a controller generating a larger preceding time of the motor command may exhibit a better performance, i.e., a smaller body sway. Regardless of the control mechanism, the delay in the control system is one of the major destabilizing factors. Therefore, a control strategy that can generate a preceding motor command must be beneficial in terms of overcoming the delay. In our previous studies [3, 18, 19], we demonstrated that a linear control strategy with a large derivative gain can stabilize the body during quiet standing in spite of a long time delay in the system. As the applied model was a conceptual one, our previous result only suggests that a control strategy that produces a motor command with a large 'body-velocity-proportional' component can generate a large preceding time of the motor command. Such body-velocity-proportional component could, however, result from an internal model [22] or an adaptive feedback control mechanism [23, 24]. Therefore, the actual neural control system that generates the preceding motor command should be investigated in future studies. Nevertheless, it has to be emphasized based on the present findings that such preceding motor command is beneficial for body stabilization during quiet standing and, hence, for enhanced standing balance abilities.

Age-related changes in the CNS can reduce postural stability [15, 20]. Accordingly, we expected to also find age-related differences in TS and/or the relationship between TS and sway size. Contrary to our expectations, however, TS was not found to be different for the elderly when compared to the young. Since, in addition, sway size has not been found to be different between the two age groups (e.g., [25]), it is reasonable that also the relationship between TS and sway size is similar for the two age groups. Although many studies suggested that the elderly are applying a different control strategy during quiet standing than the young (e.g., [25]), the particular control aspect associated with TS is a common feature in both the young and elderly.

Although it is most likely that the control strategy affects the preceding time, it should be noted that the preceding time can be affected by other factors such as the delay in the feedback loop and the frequency components of body sway and internal noise. For example, van der Kooij et al. (2005) demonstrated in a theoretical study that the internal noise properties (i.e., frequency distribution) and the entry point of the noise (e.g., sensory noise or mechanical disturbance) could affect TS. The fact that considerable variation was found in the relationship between TS and COM_{RMS} (Fig. 2B), and the fact that two subjects showed atypical cross-correlations may indicate that other factors influence TS. As such, further studies including a system identification analysis [26] are required to identify the effects of other factors on TS. In the long run, the analysis performed in the present study may, however, have an advantage in assessing the balance ability in clinical practice: it is more cost-efficient to measure TS during quiet standing than to perform a system identification that requires a precise and costly perturbation system.

In conclusion, we demonstrated that sway size is correlated with the time shift between motor command and body sway, i.e., that a smaller sway size is associated with a longer preceding time. The obtained result suggests that a control strategy generating a larger preceding time can stabilize the body more effectively. This result was found in both the young and elderly, suggesting that the particular control aspect associated with TS is a common feature in both age groups.

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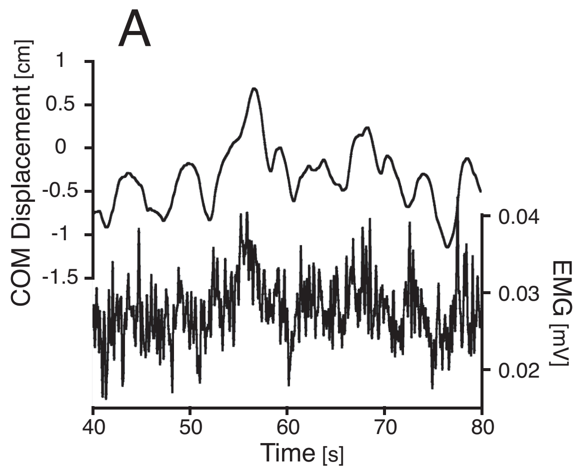
Table 1 Summary of COM_{RMS}, CC, and TS for each age group and for both age groups combined.

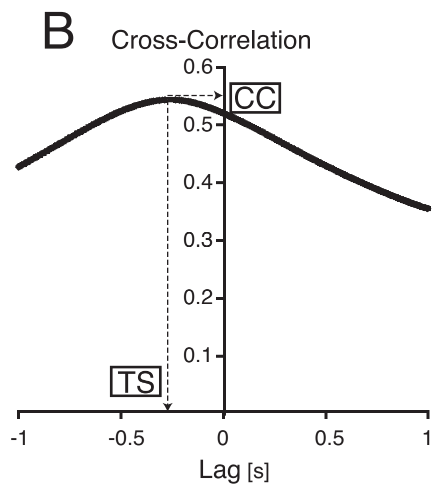
	COM_{RMS} [cm]	CC	TS [s]
Young (n = 25)	0.539±0.191	0.503±0.228	-0.244±0.111
Elderly (n = 22)	0.524±0.150	0.490±0.160	-0.216±0.065
All (n = 47)	0.532±0.172	0.497±0.197	-0.231±0.092

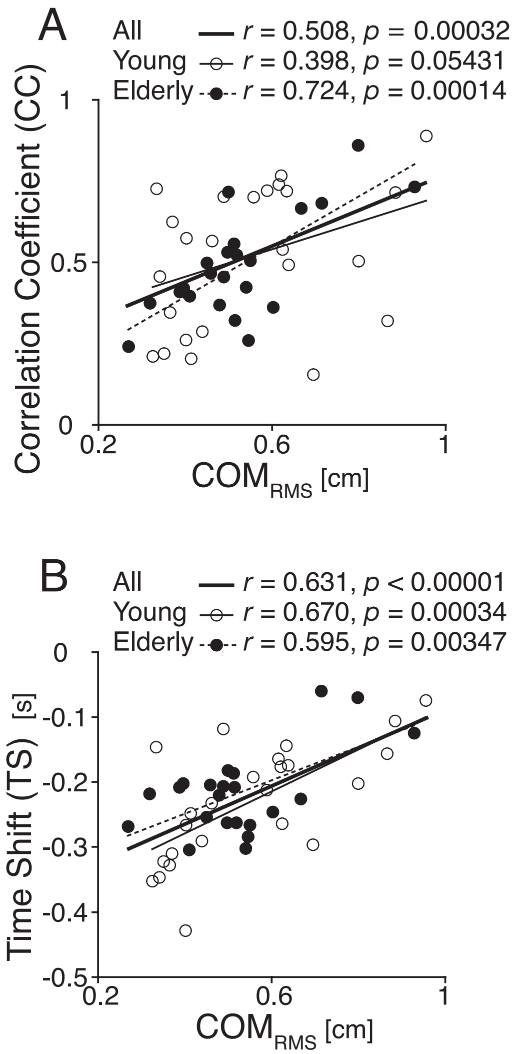
Figure Legends

Fig. 1 A: Example recordings for one subject. The traces indicate the COM displacement (top) and the rectified and filtered soleus EMG (bottom). Note that only an excerpt of the time series is shown to reveal the signal characteristics. B: Example of cross-correlation function between the COM displacement and muscle activity. Only the part around the peak of the cross-correlation is presented, which was used to determine CC and TS.

Fig. 2 Relationship between CC and COM_{RMS} (A), and between TS and COM_{RMS} (B). The lines in each plot indicate the linear regressions to visualize the linear relationship between the parameters.


A
COM Displacement [cm]
1
0.5
0
-0.5
-1
-1.5
0.04
0.03
0.02
EMG [mV]
40
50
60
70
80
Time [s]


B
Cross-Correlation
0.6
0.5
0.4
0.3
0.2
0.1
CC
TS
-1
-0.5
0
0.5
1
Lag [s]


A
All r = 0.508, p = 0.00032
Young r = 0.398, p = 0.05431
Elderly r = 0.724, p = 0.00014
Correlation Coefficient (CC)
1
0.5
0
0.2
0.6
1
COMRMS [cm]
B
All r = 0.631, p < 0.00001
Young r = 0.670, p = 0.00034
Elderly r = 0.595, p = 0.00347
Time Shift (TS) [s]
0
-0.1
-0.2
-0.3
-0.4
-0.5
0.2
0.6
1
COMRMS [cm]