Gait & Posture 55 (2017) 31–36

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Full length article

Ankle muscle co-contractions during quiet standing are associated with decreased postural steadiness in the elderly

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ARTICLE INFO

Keywords:
Aging
Center of mass
Center of pressure
Co-contractions
Muscle activity
Posturography
Standing

ABSTRACT

It has been reported that the elderly use co-contraction of the tibialis anterior (TA) and plantarflexor muscles for longer duration during quiet standing than the young. However, the particular role of ankle muscle co-contractions in the elderly during quiet standing remains unclear. Therefore, the objective of this study was to investigate the association between ankle muscle co-contractions and postural steadiness during standing in the elderly. Twenty-seven young (27.2 ± 4.5 yrs) and twenty-three elderly (66.2 ± 5.0 yrs) subjects were asked to stand quietly on a force plate for five trials. The center of pressure (COP) trajectory and its velocity (COPv) as well as the center of mass (COM) trajectory and its velocity (COMv) and acceleration (ACC) were calculated using the force plate outputs. Electromyograms were obtained from the right TA, soleus (SOL), and medial gastrocnemius (MG) muscles. Periods of TA activity (*TAon*) and inactivity (*TAoff*) were determined using an EMG threshold based on TA resting level. Our results indicate that, in the elderly, the COPv, COMv, and ACC variability were significantly larger during *TAon* periods compared to *TAoff* periods. However, in the young, no significant association between respective variability and TA activity was found. We conclude that ankle muscle co-contractions in the elderly are not associated with an increase, but a decrease in postural steadiness. Future studies are needed to clarify the causal relationship between (1) ankle muscle co-contractions and (2) joint stiffness and multi-segmental actions during standing as well as their changes with aging.

1. Introduction

Characteristics of postural steadiness during quiet standing have been used widely in research and clinical practice to quantify postural balance abilities in different populations [1–4]. In this context, many studies over the last two decades have shown that the elderly exhibit lower postural steadiness during quiet standing than the young, and this in terms of a larger center of pressure (COP) displacement [1,3–5], a larger COP velocity [1,3–5], and a larger center of mass (COM) acceleration [3,5]. More importantly, strong evidence exists that: (1) medial-lateral measures of postural steadiness are predictive of fall risk; and (2) anterior-posterior and medial-lateral measures of postural steadiness in the elderly can distinguish fallers from non-fallers [2,6]. Falls, however, are a serious concern considering the potential implications of falling for affected individuals' health and quality of life [7]. Due to this reason, mechanisms underlying age-related changes in postural steadiness during quiet standing have been investigated extensively, with numerous studies focusing on the time-varying characteristics of the aforementioned COP and/or COM variability [2,6,8,9].

During quiet standing, the COP variability is approximately proportional to the ankle joint torque variability, whose primary task is to

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http://dx.doi.org/10.1016/j.gaitpost.2017.03.032
Received 17 March 2016; Received in revised form 2 March 2017; Accepted 30 March 2017
0966-6362/

regulate the body's COM position [10,11]. Since the COM is located in front of the ankle joint during quiet standing, a continuous ankle extension or plantarflexor joint torque is needed to stabilize the ankle joint and the COM. Therefore, the plantarflexors and especially the soleus muscles are continuously active to provide the required plantarflexion torque. In addition, in healthy *young* individuals, the dorsiflexors such as the tibialis anterior muscles are rarely activated during quiet standing [12,13]. In healthy *elderly* individuals, however, the tibialis anterior muscles are frequently activated during quiet standing [14,15], which directly results in frequent co-contractions between the plantarflexors and dorsiflexors [14].

Co-contractions in general and those described above in particular are assumed to increase respective joint stiffness. In fact, single joint examinations of the ankle joint have demonstrated that activation of plantarflexors [16] and dorsiflexors [17] positively correlates with ankle joint stiffness. Therefore, co-contractions of plantarflexors and dorsiflexors may increase ankle joint stiffness in a similar matter as stays of a sailboat support the mast − a concept that has been used to describe the mechanisms involved in human trunk stability [18]. Indeed, Carpenter et al. [19] demonstrated in healthy young individuals that the postural threat induced by changes in base of support height leads to ankle muscle co-contractions, which increase ankle joint stiffness.

In light of these considerations, it would be reasonable to assume that co-contractions frequently observed in the elderly contribute to increased ankle joint stiffness during quiet standing. Since elderly individuals are believed to have inferior postural balance abilities in comparison to the young, such increase in ankle joint stiffness should also affect their postural steadiness as measured by COP and COM variability. Note that these dependencies are supported by the aforementioned study in healthy young individuals [19], where ankle muscle co-contractions induced by the postural threat reduced the variability of both COP and COM (measured via standard deviation) while increasing the mean power frequency of COP.

In spite of the known relation between ankle muscle co-contractions and postural steadiness for the task described in [19], the particular role of ankle muscle co-contractions in the elderly during quiet standing remains unclear. Insights on this role are, however, of substantial interest given the overall decrease in postural steadiness in the elderly in comparison to the young. Therefore, the objective of this study was to quantify the association between ankle muscle co-contractions and postural steadiness during quiet standing and to characterize the effect of aging on this relationship.

2. Methods

2.1. Subjects

Experimental data were acquired in the context of a previous study [20]. Twenty-seven healthy young adults (14 female; age: 27.2 ± 4.5 years; height: 168 ± 9 cm; weight: 62.3 ± 10.9 kg) and twenty-three healthy elderly adults (12 female; age: 66.2 ± 5.0 years; height: 157 ± 7 cm; weight: 59.3 ± 8.4 kg) participated in this study. They had no medical history of neurological disorders. All subjects gave their written informed consent to participate in the study, whose experimental procedures were approved by the local ethics committee.

2.2. Procedure

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 quietly and to refrain from any voluntary movements. Each subject completed five trials with sufficient resting time in between the trials. A force platform (Type 9281B, Kistler, Switzerland) was used to measure the ground reaction force during quiet standing. Surface electromyograms (EMGs) were recorded from the right tibialis anterior muscle (TA), soleus muscle (SOL), and medial (MG) and lateral (LG) heads of the gastrocnemius muscle. The EMGs were amplified and band-pass filtered between 20 and 500 Hz (Bangnoli 8 EMG System, Delsys, Boston, MA). Due to the similarity of the MG and LG activation profiles, the EMG of LG was not further analyzed in this study. In addition, postural sway data from a laser displacement sensor was acquired for the purpose of a previous study [20] and not further processed. Note that this study revealed a smaller sway size during standing being associated with a longer time shift between soleus EMG and COM fluctuations for both the young and elderly. In the present study, all data were sampled at 1 kHz and stored on a personal computer for subsequent analyses. Prior to the standing task, resting EMG levels were recorded in a seated posture for 30 s.

2.3. Data processing

We focused on the analysis of the anterior-posterior direction given that TA with its particular geometric configuration primarily contributes to body stabilization in this direction. The ground reaction force components obtained from the force plate were low-pass filtered with a cutoff frequency of 30 Hz using a fourth-order Butterworth filter. They were used to calculate the COP displacement, and the COP velocity (COPv) was identified using numerical differentiation of the COP displacement. The COM displacement and its velocity (COMv) were estimated using the Gravity Line Projection Method as described by Zatsiorsky and King [21]. The COM acceleration (ACC) was estimated using the horizontal force obtained from the force plate, according to:

$$ACC = \ddot{x}_{COM} \approx f_{AP}/m, \quad (1)$$

where f_{AP} denotes the horizontal force in the anterior-posterior direction and m denotes the subject's body mass M without his/her feet as modeled by $m = 0.971 \cdot M$ [22].

The EMGs of TA, SOL, and MG were rectified and smoothed using a fourth-order Butterworth filter with a low-pass cutoff frequency of 1 Hz. Then, the temporal phases, or periods, in the smoothed time series data were identified for which TA was either active (*TAon*) or inactive (*TAoff*). To identify the boundaries of these periods, we used several thresholds based on the TA resting level as obtained during seated posture. First, the standard deviation of the TA resting level (SD_{TA}) was calculated. Then, a range of thresholds was identified using the *average TA resting level* + *3, 5, 7, 9, or 11* · SD_{TA}. Finally, *TAon* and *TAoff* periods were obtained based on the smoothed EMG of TA being above or below the applied threshold, respectively. While we analyzed the experimental data using all five stated thresholds, we primarily present results for the *average TA resting level* + *3* · SD_{TA}, unless specifically mentioned, as we reached the same conclusions for other thresholds. Note that the applied threshold criterion was also used by Laughton et al. when examining muscle co-contractions during quiet standing [14].

2.4. Data analysis

The duration of *TAon* periods was expressed as a percentage of the entire period of standing (90 s). As this percentage was limited between 0 and 100%, whose parent distribution is non-normal, we compared *TAon* periods between the age groups using Wilcoxon's rank-sum test (non-paired). Subjects who exhibited TA activity for the entire period of standing (i.e., 100% *TAon*) were excluded from subsequent analyses. The variability of COP, COPv, COM, COMv, and ACC was quantified using the standard deviation. The amount of muscle activation of TA, SOL, and MG was quantified using the mean amplitude of each filtered EMG. Then, for each age group separately, the variability of COP, COPv, COM, COMv, and ACC as well as the mean amplitudes of TA, SOL, and MG were compared between *TAon* and *TAoff* periods using Wilcoxon's signed-rank test (paired) and Bonferroni correction, as we found non-normal presentation in 5 out of 32 sample distributions of the tested parameters (Kolmogorov-Smirnov tests). We also calculated

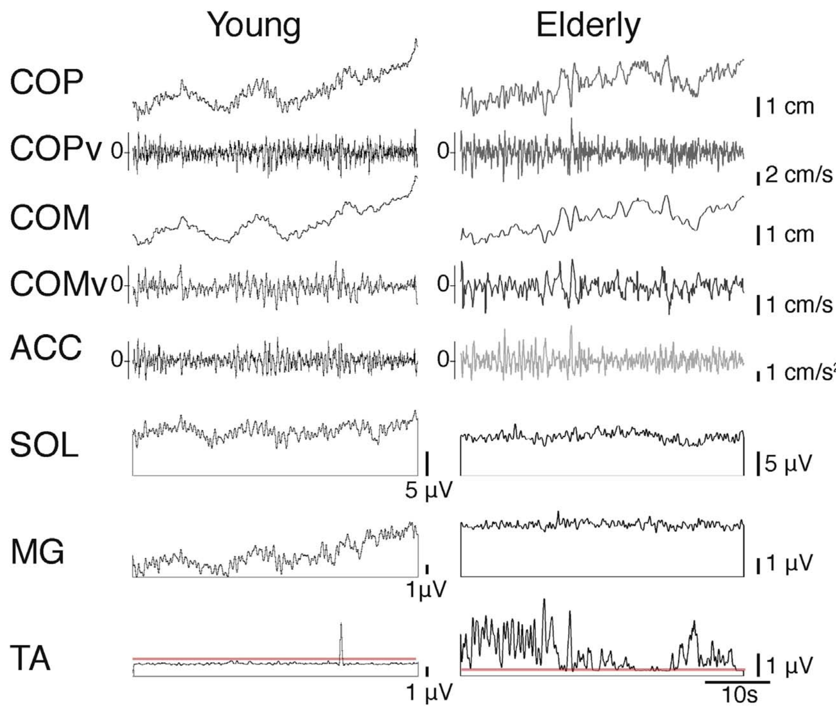

Fig. 1. Typical examples of the time series data for the force plate-based (COP, COPv, COM, COMv, and ACC) and EMG (SOL, MG, and TA) measures for the young (left) and the elderly (right). Postural sway as measured by COM, COMv, and ACC as well as the level of underlying control as measured by COP and COPv appeared to be larger in the elderly compared to the young. It can also be seen that TA activity was more prominent in the elderly, with the the horizontal line marking the threshold for quantifying *TAon* and *TAoff* periods (via the *average TA resting level* + 3 · SD_{TA}).

the mean distances of COP and COM from the ankle joint for each TA period and age group. A two-way repeated measure analysis of variance (ANOVA) was used for each of the COP and COM mean anterior-posterior distances from the ankle joint after normality was confirmed. A statistical software package (SPSS Statistics ver. 22, IMB Corp., USA) was used for all statistical tests. $p < 0.05$ served as the level of statistical significance.

3. Results

Typical examples of the time series data for the force plate-based and EMG measures are depicted for both age groups in Fig. 1. In general, postural sway as measured by COM, COMv, and ACC as well as the level of underlying control as measured by COP and COPv appeared to be larger in the elderly compared to the young. In addition, Fig. 1 exemplifies that TA activity was more prominent in the elderly, with the red line marking the threshold for quantifying *TAon* and *TAoff* periods. It should also be emphasized that the recruitment of TA did not result in complete inactivity of the antagonists, i.e., SOL and MG were still active during *TAon*, suggesting that both plantarflexors and dorsiflexors were co-contracted in both age groups during *TAon* periods.

Fig. 2A indicates, for each age group and each threshold tested, the duration of *TAon* periods when expressed as a percentage of the entire period of standing. As expected, the choice of threshold affected the percentage of *TAon* periods, i.e., when the threshold was larger, the percentage of *TAon* periods was smaller. Irrespective of the chosen threshold, the elderly showed significantly longer periods of TA activity than the young ($p < 0.001$ for all comparisons). More specifically, the median percentage of *TAon* periods ranged from 82.7 to 91.5% for the elderly and from 5.2 to 19.0% for the young (11 SD_{TA} to 3 SD_{TA} for both age groups). Seven elderly subjects who exhibited continuous TA activity throughout the entire period of standing (i.e., 100% *TAon*) were excluded from subsequent analyses. Thus, experimental data from 27 young and 16 elderly subjects were used moving forward.

Fig. 2B–D shows group results of the mean amplitudes of TA (B), SOL (C), and MG (D) when comparing between *TAon* and *TAoff* periods. TA activity was significantly higher during *TAon* than during *TAoff* in both the young ($p < 0.0001$) and elderly ($p < 0.0001$). SOL activity was not significantly different between *TAon* and *TAoff* periods for both the young ($p = 0.999$) and the elderly ($p = 0.807$). Similarly, MG activity was not significantly different between *TAon* and *TAoff* periods for both the young ($p = 1.000$) and the elderly ($p = 0.386$).

Fig. 3 shows group results of the variability of COP (A), COPv (B), COM (C), COMv (D) and ACC (E) when comparing between *TAon* and *TAoff* periods as well as between age groups. The Wilcoxon signed-rank tests revealed that, between *TAon* and *TAoff* periods: (1) the variability of COP and COM was different for both age groups (COP: $p = 0.0004$ for the young and $p = 0.031$ for the elderly; COM: $p = 0.0003$ for the young and $p = 0.043$ for the elderly); and (2) the variability of COPv, COMv, and ACC was different in the elderly only (COPv: $p = 1.000$ for the young and $p = 0.022$ for the elderly; COMv: $p = 0.172$ for the young and $p = 0.049$ for the elderly; ACC: $p = 0.233$ for the young and $p = 0.010$ for the elderly).

Table 1 shows the COP and COM mean anterior-posterior distances from the ankle joint. No significant main effects and interactions were found for both applied ANOVAs.

4. Discussion

4.1. Ankle muscle co-contractions in the elderly and their association with postural steadiness during quiet standing

Our work is complementary to previous efforts demonstrating that TA activity is higher in the elderly than the young during standing [14,15] (Fig. 1). In addition, our study clearly indicates the prevalence of *TAon* over *TAoff* periods in the elderly, whereas the opposite is true for the young regardless of the selected threshold (Fig. 2A). In this context, the significant difference in TA activity for the *TAon* and *TAoff* categories in both age groups (Fig. 2B) confirmed the use of an adequate TA thresholding method. Of higher conceptual interest, however, is the fact that, in both age groups, TA activity comes paired

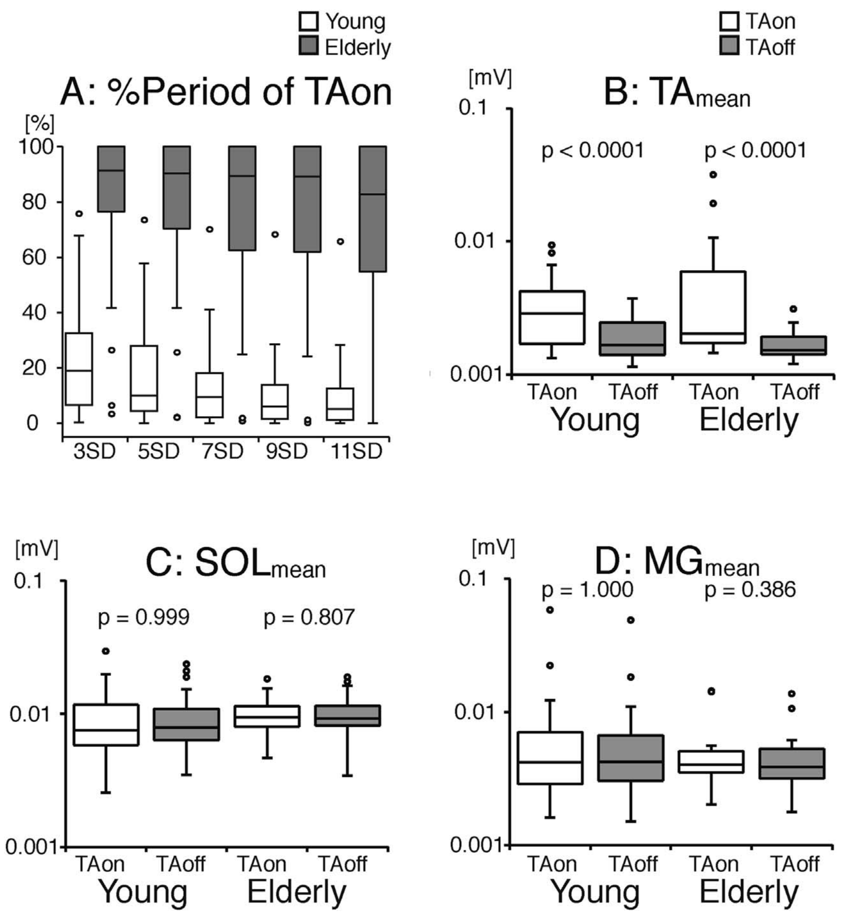

Fig. 2. The duration of *TAon* periods when expressed as a percentage of the entire period of standing is shown in (A) for each age group and each threshold separately. The group results of the mean amplitudes of TA, SOL, and MG when comparing between *TAon* and *TAoff* periods are shown in (B), (C), and (D), respectively. Significance results (*p*-values) of Wilcoxon's rank-sum (*TAon* periods) and signed-rank (EMG amplitude means) tests are shown within each subplot.

with plantarflexor activity that has not been significantly reduced in comparison to *TAoff* periods (Fig. 2C and D). This indicates that, during *TAon* periods, individuals standing quietly must experience typical ankle muscle co-contractions.

For stated ankle muscle co-contractions during *TAon*, the variability of COP and COM was significantly larger in the elderly in comparison to periods of pure plantarflexor activity (*TAoff*; Fig. 3A and C). In accordance with the commonly assumed inverse proportionality of postural steadiness with time-domain characteristics of the COP and COM time series during standing [1,3–5], this presumably suggests decreased postural steadiness in the elderly during TA activity. However, one has to be careful with such conclusion due to the properties of the underlying signals. Among the obtained force plate time series, the COP and COM data are comparably non-stationary over shorter periods of time due to their fractal properties [23], resulting in increased variability with increased data length. Therefore, the significantly larger COP and COM variability for *TAon* periods in comparison to *TAoff* periods in the elderly is certainly affected by the significantly longer *TAon* segment lengths. Note that the opposite is true for the young, where the longer *TAoff* periods indicate a significantly larger variability for exactly the COP and COM time series (Fig. 3A and C). Thus, results associated with the COP and COM variability are highly biased and unreliable when comparing measurement periods of significantly different length.

In contrast to COP and COM, the time series of COPv, COMv and ACC are rather stationary in both the short- and long-term (see Fig. 1), implying that data length will not significantly affect their quantified variability. As a consequence, the significantly larger variability of COPv, COMv, and ACC in the elderly during *TAon* periods (Fig. 3B, D, and E) confirms our initial conclusion that ankle muscle co-contractions in the elderly are associated with decreased postural steadiness [1,3–5] when quantified by these metrics. These results in the elderly are also supported by those in the young: if the differences in the COPv, COMv, and ACC variability in the elderly were due to the time series' variability being affected by *TAon* versus *TAoff* segment lengths, one would also expect a significantly lower variability during *TAon* periods in the young (similar to what was seen in COP and COM). However, since this was not the case (Fig. 3B, D, and E), we can associate the larger variability of COPv, COMv, and ACC in the elderly during *TAon* periods with an actual decline in postural steadiness [1,3–5]. Consequently, also ankle muscle co-contractions due to frequent TA activation in the elderly are associated with a decrease in postural steadiness as measured by COPv, COMv, and ACC variability.

The obtained findings agree with previous findings of Warnica et al. [24] who showed that an increase in *voluntary* co-contractions during standing were associated with an increase of COM and COP velocities. However, this relationship was only found at high levels of co-contraction (i.e., 30–40% of maximum voluntary contractions) that are usually not observed during quiet standing [14]. Further, our results also agree with those by Carpenter et al. [19] who reported that co-contractions induced by the applied postural threat increased the mean power frequency of COP, which presumably implies an increase in COP velocity. Nonetheless, the notable uniqueness of our results is that the decrease of postural steadiness during *TAon* periods only occurred in the elderly. In this context, Laufer et al. have shown that postural threat affects measures of postural steadiness solely in the elderly [25], supporting a future hypothesis that postural threat perceived in the elderly during standing may have caused the differences between age

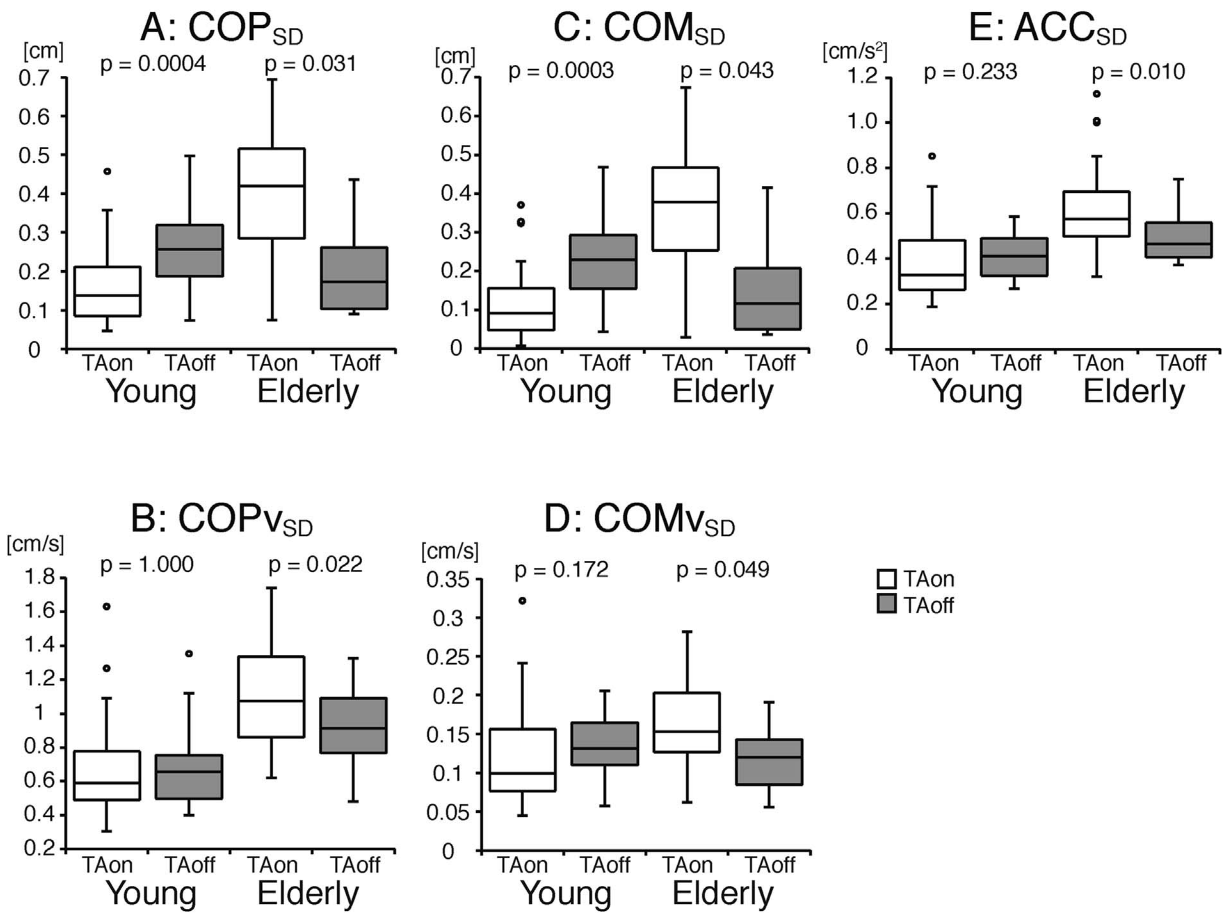

Fig. 3. Group results of the variability of COP (A), COPv (3B), COM (C), COMv (D) and ACC (E) when comparing between *TAon* and *TAoff* periods. Significance results (*p*-values) of Wilcoxon's signed-rank test are shown adjacent to each subplot.

Table 1
The mean anterior-posterior distances of the body's center of pressure (COP) and center of mass (COM) from the ankle joint center, for each age group and each period of *TAon* and *TAoff*. The two-way repeated measure ANOVA revealed no significant differences in the displacements for age group (mean COP distance: p = 0.742; mean COM distance: p = 0.742) and TA period (mean COP distance: p = 0.226; mean COM distance: p = 0.226). No interaction effects were found (mean COP distance: p = 0.827; mean COM distance: p = 0.783). In agreement with the dynamics of quiet standing, the means of the COPv, COMv, and ACC time series were found to be approximately zero for each age group and each period of *TAon* and *TAoff* (not shown).

	Mean COP distance [cm]		Mean COM distance [cm]	
	TAon	*TAoff*	*TAon*	*TAoff*
Young	5.77 ± 1.89	5.86 ± 1.61	5.78 ± 1.89	5.86 ± 1.62
Elderly	5.60 ± 1.08	5.72 ± 1.08	5.60 ± 1.08	5.72 ± 1.07

groups observed in this study.

4.2. Why are ankle muscle co-contractions associated with decreased postural steadiness in the elderly?

As mentioned above, Carpenter et al. [19] demonstrated that the increase of co-contractions due to a postural threat is accompanied by an increase in COP velocity as well as an increase in ankle joint stiffness. Therefore, the decrease of postural steadiness observed in the elderly during *TAon* in comparison to *TAoff* periods may be associated with an increase in ankle joint stiffness induced by co-contractions. While the findings of Warnica et al. [24] support this logic, they found a change in postural steadiness only for comparably high levels of co-contraction that would not have occurred in our experiment. As we did not obtain measures of maximum voluntary contraction in our experiment, our results cannot be directly compared to those by Warnica et al. [24].

Although it is assumed that, based on Carpenter et al. [19], co-contractions during standing increase ankle joint stiffness, opposing opinions on this relation exist as well. Loram et al. [26,27] claimed that, during quiet standing, the tendon is the dominant source of passive joint stiffness arising from passive properties of the joint and of contracted muscles, suggesting that such co-contractions between plantarflexors and dorsiflexors would not modulate tendon and, hence, passive stiffness of the ankle joint. Warnica et al. [24] reported that, although ankle muscle co-contractions were associated with increased COM and COP velocity, an increase in passive stiffness via an ankle foot orthotic reduced COM velocity, suggesting that the effect of co-contractions is different from that associated with an increase in passive stiffness. Thus, while earlier explanations embracing an increase of stiffness due to co-contractions [19] could also be valid for our results, it remains plausible following our study that co-contractions do not affect passive joint stiffness.

If passive stiffness is unaffected by co-contractions, which mechanism is responsible for the observed difference in postural steadiness between *TAon* and *TAoff* in the elderly? Warnica et al. [24] found in their experiments that, during co-contractions, body movement was more reliant on hip or mixed strategies [24]. It is known that, although the body dynamics during quiet standing can be simplified by a single-link inverted pendulum [28], body movement is rather multi-segmental even during this quasi-static task [29–31]. Further, the segmental actions of the upper and lower segments directly affect the amount of body acceleration [29,31]. However, the elderly have difficulties in regulating these multi-segmental actions and, hence, in reducing body acceleration [31], potentially due to a decreased ability to detect heel pressures [32], passive joint motions [33], and/or differences in joint velocities [34]. Consequently, co-contractions may be associated with the body's segmental actions, and the elderly's inability to control these segmental actions may be enhanced during *TAon* periods. In this case, ankle muscle co-contractions are not causally linked to changes in ankle joint stiffness, but are paired with a specific postural strategy that reveals, via measures of postural steadiness, neuromuscular control changes with aging.

5. Conclusion

The present study quantified the relationship between ankle muscle co-contractions and measures of postural steadiness in the elderly. By separating periods of TA activity from those of TA inactivity, we demonstrated that ankle muscle co-contractions in the elderly are not associated with an increase, but a decrease in postural steadiness.

Conflict of interest

There are no known conflicts of interest.

Acknowledgements

The authors acknowledge the support of the Toronto Rehabilitation Institute − the University Health Network, which receives funding under the Provincial Rehabilitation Research Program from the Ministry of Health and Long-Term Care in Ontario. The study was supported in part by the Grants-in-Aid Program for Scientific Research from the Japan Society for the Promotion of Science (No. 16500370) and a Canadian Institutes of Health Research − STIHR Fellowship in Health Care, Technology, and Place.

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