

(i) Title: Larger Center of Pressure Minus Center of Gravity in the Elderly Induces Larger Body Acceleration during Quiet Standing

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Abstract

When an inverted pendulum approximates quiet standing, it is assumed that the distance between the center of pressure and the vertical projection of the center of mass on the ground (COP-COG) reflects the relationship between the controlling and controlled variables of the balance control mechanism, and that the center of mass acceleration (ACC) is proportional to COP-COG. As aging affects the control mechanism of balance during quiet standing, COP-COG must be influenced by aging and, as a result, ACC is influenced by aging as well. The purpose of this study was to test the hypotheses that aging results in an increased COP-COG amplitude and, as a consequence, that ACC becomes larger in the elderly than the young. Fifteen elderly and eleven young subjects stood quietly on a force platform with their eyes open or closed. We found that: 1) the standard deviations of COP-COG and ACC were larger in the elderly than in the young, irrespective of the eye condition; 2) COP-COG is proportional to ACC in both age groups, i.e., the inverted pendulum assumption holds true for quiet standing. The results suggest that a change in the control strategy that is due to aging causes a larger COP-COG in the elderly and, as a consequence, that ACC becomes larger as well.

Key Words: Standing, Equilibrium, Center of Pressure, Center of Mass, Center of Gravity

Introduction

Since the human body is inherently unstable, a control system is required to stabilize the body even during quiet standing. Active control provided by the central nervous system as well as passive mechanical stabilization contribute to stabilizing the body [17, 18, 22, 24, 27]. Age-related changes in the central nervous system and the musculoskeletal system can influence various functions of this control mechanism, and, as a result, can reduce postural stability [12, 21]. Such age-related changes in postural stability during quiet standing have been investigated using time-varying characteristics of the center of pressure (COP) and/or the center of mass (COM) [2, 8, 11, 19, 20, 25, 26, 29]. These measures have been associated with falling in the elderly [19, 20], which is one of the serious health problems related to aging.

Frequently used measures are the statistical measures of COP and COM in the time domain, such as their standard deviation or mean velocity, or in the frequency domain, such as their total power or the median frequencies [11, 13, 29, 30]. Several studies have focused on the association between COP and the vertical projection of COM (COG), using the distance between COP and COG (COP-COG) as the variable that provides a good assessment of spontaneous sway during quiet standing [3, 4, 5, 6, 7, 31, 32, 1]. Corriveau and his colleagues reported that the root mean square of COP-COG is larger in the elderly who have neurological impairments [3] as well as in stroke patients [6] when compared to healthy elderly individuals. They also discovered that physiological factors, such as peripheral somatosensory input and muscle strength, influence the amplitude of COP-COG in healthy elderly individuals and the elderly with neurological impairments [7]. These studies suggest that a neurological impairment pertaining to the control of quiet standing enlarges the COP-COG amplitude.

COP-COG is the variable that reflects the relationship between the controlling and controlled variables in the control mechanism of quiet standing when approximated using an inverted pendulum model. If human posture during quiet standing can be approximated by an inverted pendulum, the equation of motion is described as

$$I\ddot{\theta} = mgh\sin\theta - T, \quad (1)$$

where m is the mass of the body without the feet, g is the gravitational acceleration coefficient, h is the

distance between COM and the ankle joint, I is the moment of inertia of the body about the ankle joint, θ is the body angle to the vertical axis, $\ddot{\theta}$ is the body angular acceleration, and T is the ankle torque produced by the subject about the ankle joint. From the view of the control mechanism, T is the controlling variable, whereas θ is the controlled variable. Assuming that the body sway amplitude is small, $T \approx mgCOP$ and $mgh\sin\theta = mgCOG$. Therefore, both COP and COG (since $\sin\theta \approx \theta$ for small angles) are approximately proportional to the controlling variable. Since the relationship between the controlling and controlled variables is sensitive to changes in the control system, it is assumed that COP-COG is sensitive to the change of the control system. As such, the abovementioned previous studies imply that the increment of COP-COG is due to the alteration of the control strategy caused by the neurological impairments. However, only a few studies to date have compared COP-COG between the healthy elderly and the young. Accordingly, we suggest in the present study that a potential hypofunction of the motor control strategy due to aging could be detectable by this measure.

The right-hand side of equation (1) can be rewritten as $-mg(COP-COG)$. Then, considering an additional approximation of $\ddot{\theta} \approx C\ddot{O}M/h = ACC/h$, one can derive

$$COP-COG = -\frac{I}{mgh}ACC \quad (2)$$

where ACC is the horizontal COM acceleration [34]. Equation (2) expresses that COP-COG is proportional to ACC . Therefore, if COP-COG is enlarged by the alteration of the control strategy due to aging, the increment of the COP-COG amplitude will result in an increment of the ACC amplitude.

The purpose of this study was to test the hypotheses that aging results in an increased COP-COG amplitude and, as a consequence, that ACC becomes larger in the elderly than the young.

Materials and Methods

Fifteen healthy elderly male subjects (72.7 ± 5.6 yrs, mean \pm SD age) and eleven healthy young male subjects (29.0 ± 7.7 yrs) participated in this study. At the time of the experiments, the subjects reported having no neurological or musculoskeletal impairments, and were living independently in the community.

All subjects gave written informed consent according to the principles of the Declaration of Helsinki, which was approved by the local ethical committee. Each subject was asked to maintain a quiet stance posture standing barefoot with eyes open (EO) and closed (EC). The subjects had their arms hanging along the sides of their body, their feet were parallel and the distance between their heels was 15 cm. One trial was performed for each visual condition. The order of application of EO and EC conditions was randomized among the subjects. The duration of each trial was approximately 70 s, and data from the latter 60 s were subjected to subsequent analyses. A sufficient resting time was allowed between trials. Note that we focused only on the anterior-posterior direction of sway in this study. A force platform (Type 9281B, Kistler, Switzerland) was used to measure the subjects' COP displacement and the horizontal ground reaction force during quiet standing. All data were sampled at 1 kHz using a 16 bit analog-to-digital converter (PowerLab, ADInstruments, New Zealand). The anthropometric estimation of body dimensions was based on [33]: $h=0.547H$, where H indicates the subject's height; $m=0.971M$, where M indicates the subject's body mass; $I=0.319MH^2$.

To obtain the COM displacement, we adopted the *zero-point-to-zero-point double integration technique* or *gravity line projection method*. This method has initially been proposed by King and Zatsiorsky [15] and has been described in more detail in a later work [35]. It is based on the premise that COP and COG coincide when ACC, calculated using the horizontal force, is equal to zero. Using this premise, we were able to obtain the discrete COG at the instances when ACC was equal to zero. These discrete COG points were connected by calculating the double integral of ACC obtained via the horizontal force. For this analysis, all kinematic and kinetic data were low-pass filtered using a fourth-ordered, zero-phase-lag Butterworth filter [33] with a cutoff frequency of 10 Hz according to [16]. COP-COG was calculated using the COP and COG time series. ACC was calculated using the horizontal force time series, i.e., $ACC=f_h/m$. We quantified the fluctuation amplitude of all variables using the standard deviation (SD) for each trial. The SDs of COP, COG, ACC, and COP-COG were used in the subsequent statistical analysis. We also tested how well ACC, estimated from COP-COG using equation (2), corresponded to the actual ACC obtained in the experiments. Linear regression analysis was used to evaluate the relationship between the SD of the actual ACC and the SD of the ACC estimated from COP-COG. In the regression analysis, the data from EO and EC were pooled, while the regression analysis was done separately for each

age group. The effects of age and eye conditions were analyzed using two-way repeated measures ANOVA with a within-subject factor of eye condition and a between-subject factor of age for each variable. $P < 0.05$ was used as a level of significance to prevent excessive false-positive results.

Results

Fig. 1 shows examples of COP, COG, COP-COG, and ACC data for a young subject (left panel) and an elderly subject (right panel) for the EC condition. Note that only 15 s of data out of the analyzed 60 s are presented in the figure to isolate the signal features. The features of COP and COG resembled each other closely. However, the COP was slightly larger than COG as it fluctuated around COG. The features of COP-COG resembled the inverse form of ACC well. Comparing the data between the young and elderly subjects, one can see that the COG amplitude seemed similar, whereas COP showed a larger deviation from COG in the elderly than in the young. The larger deviation in the elderly became more evident when the time series of COP-COG and ACC were compared between the age groups: Both time series appeared distinctly larger in the elderly than in the young.

Fig. 2 shows group mean values of SD of COP, COG, ACC, and COP-COG for each age group and eye condition. COP was significantly larger for the EC than in the EO condition ($P = 0.015$), while there was no significant difference between age groups ($P = 0.478$). There was no interaction between the factors age group and eye condition for COP ($P = 0.702$). For COG, there was no significant difference between eye conditions ($P = 0.079$) and between age groups ($P = 0.834$). ACC was significantly larger in the elderly than in the young ($P = 0.003$) and significantly larger for the EC than in the EO condition ($P < 0.0001$). There was no interaction between the factors age group and eye condition for ACC ($P = 0.055$). COP-COG was significantly larger in the elderly than in the young ($P = 0.007$), and significantly larger for the EC than in the EO condition ($P < 0.0001$). There was no interaction between the factors age group and eye condition for COP-COG ($P = 0.062$).

We compared the actual ACC determined from f_h with the ACC estimated from COP-COG in Fig. 3 for each age group. Linear regression analysis provided the regression lines of: $Y = -0.21 + 1.14X$, $R = 0.973$ for the young, and $Y = -0.04 + 1.01X$, $R = 0.976$ for the elderly (X indicates the actual ACC, and Y indicates the estimated ACC). For the young group, the 95 % confidence intervals for the slope and intercept were from 1.01 to 1.26 and from -0.34 to -0.07, respectively. For the elderly group, the 95 % confidence intervals for

the slope and intercept were from 0.93 to 1.10 and from -0.20 to 0.93, respectively. The confidence interval of the regression line of the elderly group included the line of identity, while that of the young group did not. However, note that their line was also fairly close to the line of identity despite considerable errors in the estimation of the anthropometric parameters. Thus, the result suggests that the actual ACC corresponds to the value estimated from COP-COG using the inverted pendulum model.

Discussion

We clearly demonstrated that both COP-COG and ACC are larger in the elderly than in the young irrespective of the eye condition. Since the standard deviation of the ACC fluctuation matches the one estimated from COP-COG using an inverted pendulum model, the inverted pendulum assumption was validated for the quiet standing condition in this experiment. Thus, we demonstrated that COP-COG is larger in the elderly than in the young, and, as a consequence, ACC is larger as well.

COP is proportional to the ankle torque, which is regulated by the central nervous system to restore the equilibrium of balance. COP can therefore be interpreted as the *controlling* variable of the postural control system. COM on the other hand is an imaginary point at which the total body mass can be assumed to be concentrated. The position of the COM has been hypothesized to be subject to body postural control, which is the *controlled* variable of the system. Thus, postural control during quiet stance can be characterized by the relation between the COP and the COM. Since the relationship between these controlling and controlled variables is sensitive to changes in the control system, it is assumed that also COP-COM is sensitive to such changes. Thus, the identified increase in COP-COG in the elderly strongly suggests a change in the control strategy that is due to aging.

At this stage, the age-related change in the physiological control system that is actually responsible for the present findings cannot be entirely captured. One explanation of the underlying mechanisms may be the following: Maurer and Peterka [23] demonstrated in their theoretical study that higher gain controllers or a higher driving noise level can account for the change of COP measures in aging. They simplified the postural control system using a continuous feedback strategy, in which various sensory modalities of the physiological system are integrated, yielding an estimate of the COM angle. The neural control center in their study is approximated as a PID (proportional, integral, and derivative) controller that generated the desired ankle torque. A higher gain controller, i.e., a PID controller with larger gains, represents a neural

control system that generates a large response to a certain amount of sway, which results in an overreacting system in the extreme case. Thus, they suggested that the elderly show a larger response to a certain amount of sway compared to the young. Since a higher gain controller is generally supposed to create a larger deviation of the controlling variable from the controlled variable, our result that COP-COG is larger in the elderly may imply this age-related change in the control strategy. A higher driving noise level represents a larger amount of internal disturbance torque that might be due to respiration, the heart beat, and the error in the motor command. Thus, also an increase in the driving noise level could cause a larger deviation between the controlling and controlled variables. Therefore, the current result may reflect the same change in the control strategy as in Maurer and Peterka [23], implying higher gain controllers or a higher driving noise level in the elderly. Further investigation is required to fully understand the underlying mechanisms.

To date, one study demonstrated that COP-COG is larger in the elderly than in the young [1]. They compared the measure among the young of age 22.9 ± 4.0 yrs (Y-group), the elderly of age 69.2 ± 2.4 yrs (S-group), and the elderly of age 81.2 ± 6.3 yrs (E-group). They reported that the root mean square of COP-COG in the anterior-posterior direction, which is equivalent to the standard deviation adopted in this study, is larger in the E-group than in the Y-group, while COP-COG is identical between the S-group and the Y-group. They also reported that the root mean square of COG is identical among the groups. Our elderly subjects were situated between their S-group and E-group, i.e., a t-test revealed that our elderly subjects were significantly older than their S-group, and significantly younger than their E-group ($P < 0.05$ in both tests). Thus, it is plausible that our elderly subjects showed a similar behavior as the E-group in their study, i.e., that COP-COG is larger than for the young subjects and COG is identical between the age groups. Although they used a different method to calculate COG [31, 32] and tested only the EO condition, our results agree with their finding.

We also demonstrated that the larger COP-COG accounts for the larger ACC in the elderly by validating the inverted pendulum assumption, whereas Berger et al. [1] did not. In literature, it has been investigated several times to which extent the inverted pendulum assumption fits the quiet standing posture [9, 10, 14]. Karlsson and Lanshammar [14] demonstrated that up to 90 % of the standard deviation of the COM acceleration was accounted for by the inverted pendulum model. In the present study, we also

demonstrated that the standard deviation of ACC was accounted for by the standard deviation of COP-COG. The result suggests that ACC during quiet standing was caused by COP-COG following the equation of motion of the inverted pendulum.

In the literature, many measures of spontaneous sway during quiet standing have been proposed. Several measures such as the mean velocity successfully distinguished the properties of the elderly and young [29]. However, these measures only provide a *parametric* description of the spontaneous sway and do not reflect specific physiological characteristics of the control system. As such, it is still important to investigate alternative force plate measures that can capture characteristics of spontaneous sway in the elderly, which are closely tied to the actual control system. Both COP-COG and ACC are such measures since they distinguish changes of postural sway in aging and at the same time have physiological meanings.

In conclusion, we found that: 1) the standard deviations of COP-COG and ACC were larger in the elderly than in the young, irrespective of the eye condition; 2) COP-COG is proportional to ACC in both age groups, i.e., the inverted pendulum assumption holds true for quiet standing. The results suggest that a change in the control strategy that is due to aging causes a larger COP-COG in the elderly and, as a consequence, that ACC becomes larger as well.

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Figure Legends

Fig. 1 Representative example time series of COP, COG, COP-COG, and ACC for a young subject (left panel) and an elderly subject (right panel) for EC condition.

Fig. 2 Group mean values of SD of COP (left upper panel), COG (right upper panel), ACC (left lower panel), and COP-COG (right lower panel) for each age group and eye condition. White bar indicates elderly group and black bar indicates young group. EO and EC indicate the eyes open and the eyes closed conditions, respectively. Data are group means \pm standard deviations. # indicates $P<0.05$ between age groups. * indicates $P<0.05$ between eye conditions.

Fig. 3 Comparison between the actual ACC and the estimated ACC from COP-COG for each trial. Open circle indicates EO condition, and closed circle indicates EC condition. Left panel shows plots for young subjects, and right panel shows that of elderly subjects. The bold line indicates the regression line for each age group. Linear regression analysis provided the regression lines of: $Y=-0.21+1.14X, R=0.973$ for the young, and $Y=-0.04+1.01X, R=0.976$ for the elderly (X indicates the actual ACC, and Y indicates the estimated ACC). The plots for EO and EC conditions were grouped together when calculating the regression line for each age group. Note that regression lines (thick lines) are close to the lines of identity (thin lines) in both age groups.

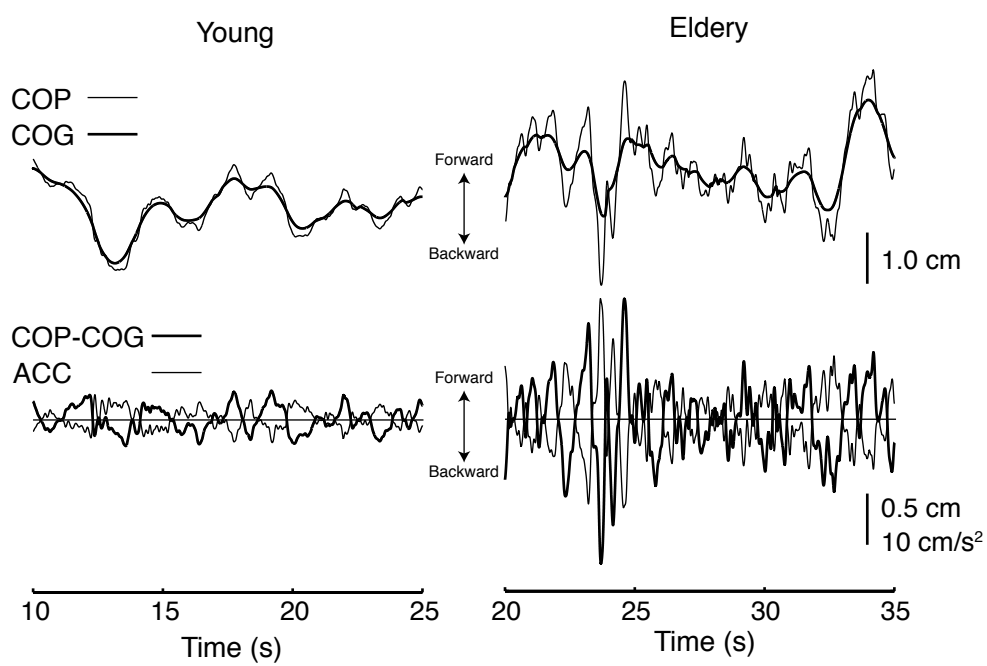


Fig. 1

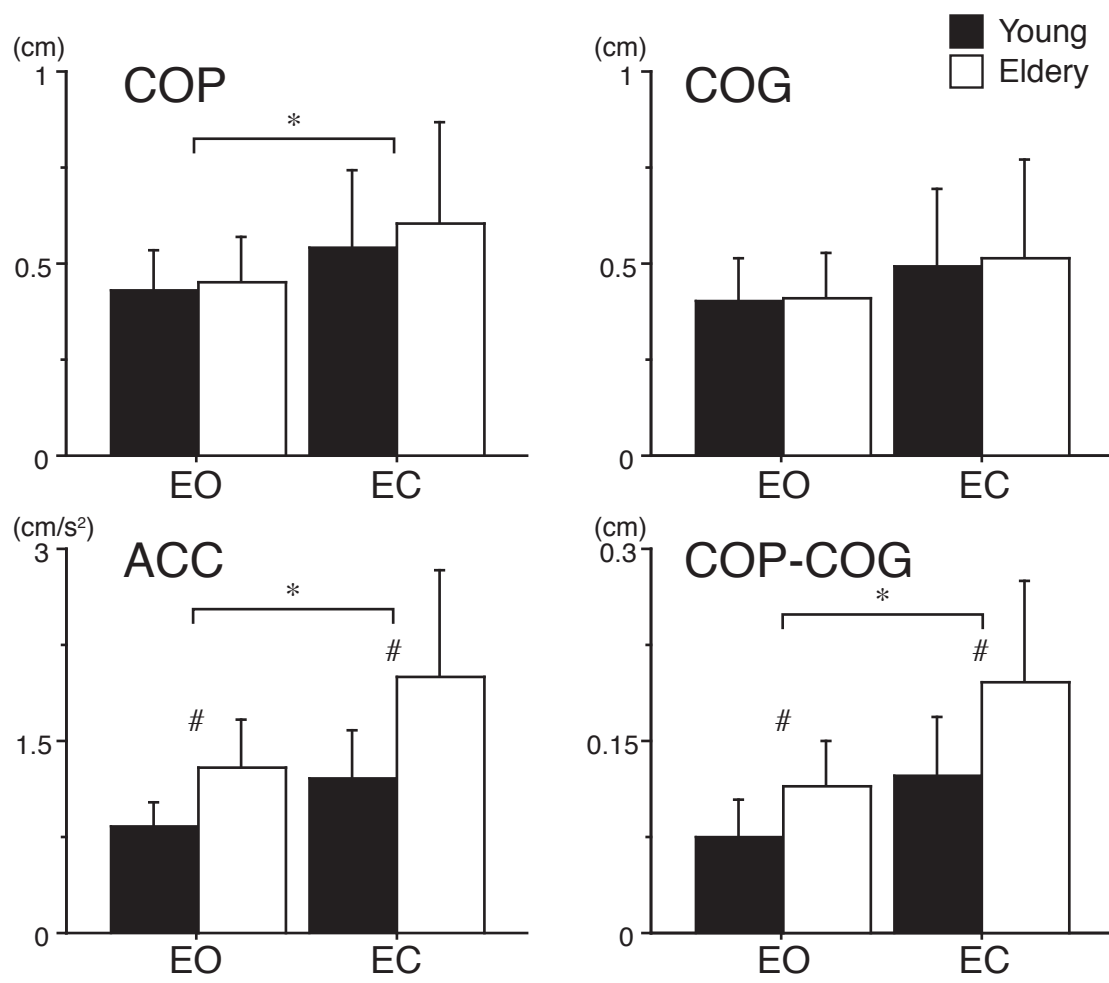


Fig. 2

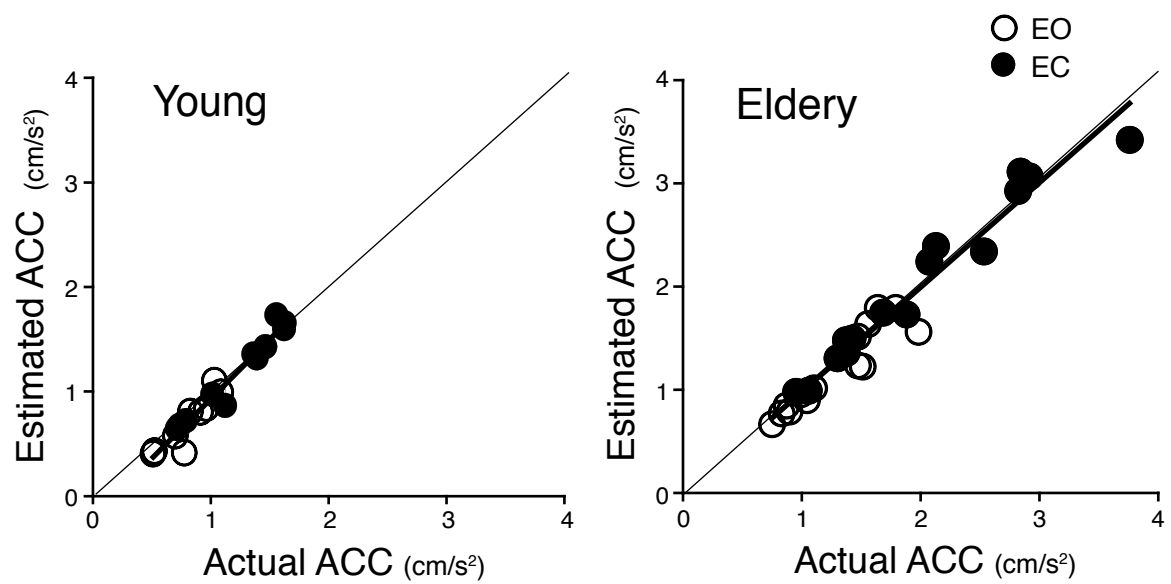


Fig. 3