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The effect of age, movement direction, and target size on the maximum speed of targeted COP movements in healthy women

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Abstract

Rapid center of pressure (COP) movements are often required to avoid falls. Little is known about the effect of age on rapid and accurate volitional COP movements. We hypothesized that COP movements to a target would be slower and exhibit more submovements in older versus younger adults, particularly in posterior versus anterior movements. Healthy older ($N = 12$, mean age = 76 years) and young women ($N = 13$, mean age = 23 years) performed anterior and posterior lean movements while standing on a force plate, and were instructed to move their COP 'as fast and as accurately as possible' using visual feedback. The results show that rapid posterior COP movements were slower and had an increased number of submovements and ratio of peak-to-average velocity, in comparison to anterior movements ($p < .005$). Moreover, older compared to younger adults were 27% slower and utilized nearly twice as many compensatory submovements ($p < .005$), particularly when moving posteriorly ($p < .05$). Older women also had higher ratios of peak-to-average COP velocity than young ($p < .05$). Thus, despite moving more slowly, older women needed to take more frequent submovements to maintain COP accuracy, particularly posteriorly, thereby providing evidence of a compensatory strategy that may be used for preventing backward falls.

Keywords

Balance; Center of pressure; Speed-accuracy trade-offs; Gerontology

1. Introduction

Rapid center of pressure (COP) movements are often required to avoid falls. Balance during upright stance requires constant adjustments of the location of the COP under the feet

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(Winter, 1990), particularly with increased age (Freitas, Wieczorek, Marchetti, & Duarte, 2005; Prado, Stoffregen, & Duarte, 2007; Prieto, Myklebust, Hoffmann, Lovett, & Myklebust, 1996). COP movements during upright stance also slow with increased age and fall-risk (Tucker, Kavanagh, Barrett, & Morrison, 2008; Tucker, Kavanagh, Morrison, & Barrett, 2009). The ability to recover from perturbations in specific directions is of significance, as the direction of a fall can be a significant predictor of the subsequent injury (Palvanen, 2000). Synchronous real-time visual feedback of COP movements has been used for patient rehabilitation as well as to assess the effect of spatial accuracy constraints on COP movement time (Danion, Duarte, & Grosjean, 1999; Duarte & Freitas, 2005; Hamman, Mekjavic, Mallinson, & Longridge, 1992; Shumway-Cook, Anson, & Haller, 1988). However, to our knowledge, the effect of age and movement direction on spatial accuracy-constrained volitional COP movements has not been well explored.

Purposeful COP movements in one direction to a given spatial target region under the foot can be termed 'discrete' movements. These differ from the continuous, often multi-directional COP movements normally used to maintain upright balance. It is possible that discrete COP movements, which can be observed during certain phases of gait initiation, and during turning and reaching (Mbourou, Lajoie, & Teasdale, 2003; Meinhart-Shibata, Kramer, Ashton-Miller, & Persad, 2005; Row & Cavanagh, 2007), are more challenging to postural control than continuous movements because of the spatiotemporal constraints, particularly in older adults. Community-dwelling older adults have demonstrated an increased risk of injury in falls when turning around or reaching (Nevitt, Cummings, & Hudes, 1991). Furthermore, previous studies have shown age-associated delays in gait initiation, which is commonly associated with falls (Henriksson & Hirschfeld, 2005). The need for rapid, accurate, and discrete COP movement arises when given a limited base of support or limited time to initiate a postural response, as has been observed among older adults (Inglin & Woollacott, 1988; King, Judge, & Wolfson, 1994).

The overall goal of this study was to determine the effect of age on discrete and rapid accuracy-constrained COP movements. Across a wide variety of tasks, Fitts' law has successfully predicted a tradeoff between accuracy and speed (for example, Fitts, 1954; Plamondon & Alimi, 1997). However, based on previous studies of whole-body COP movements (Danion et al., 1999; Duarte & Freitas, 2005), performance in these complex tasks are better predicted by the following equation:

$$W_e = a + b \cdot S$$

where S is the mean movement speed, W_e is the effective target size, and a and b are experimentally derived constants (Meyer, Abrams, Kornblum, Wright, & Smith, 1988; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). Mean movement speed can be derived from the mean movement amplitude and mean movement time, whereas the effective target size is a measure of the dispersion of the COP endpoint, defined by a multiple of the standard deviation (SD) of the COP endpoint position (i.e., $4 \cdot SD_{COP-ENDPOINT}$). Thus, movement speed is a key element of the present study as spatiotemporal parameters are constrained.

Age-related changes in COP control strategies are expected. Discrete movements may stress older versus young adult postural control disproportionately more than continuous movements. A possible mechanism is that discrete COP movements are apt to rely on sensory feedback for control (Smits-Engelsman, van Galen, & Duysens, 2002), and thus may be susceptible to decreases in foot plantar sensation and optic flow threshold sensitivity due to age (Inglis, Kennedy, Wells, & Chua, 2002; McKeon & Hertel, 2007; Wade,

Lindquist, Taylor, & Treat-Jacobson, 1995). COP movement time and corrective COP movements should increase in older versus young adults, given that older adults exhibit increased movement times and corrective movements when performing an accuracy-constrained task in the upper extremity (Ketcham, Seidler, van Gemmert, & Stelmach, 2002; Pratt, Chasteen, & Abrams, 1994), which is consistent with observations of declined motor coordination with increased age (Morgan et al., 1994). The ratio of peak-to-average velocity is an indicator of energy efficiency (Flash & Hogan, 1985; Hogan, Bizzi, Mussa-Ivaldi, & Flash, 1987; Nelson, 1983). As age-related changes have been observed in the peak-to-average velocity of targeted upper extremity movements (Meulenbroek, Vinter, & Desbiez, 1998), increases in muscle force variability and antagonist muscle coactivation in older adults (Galganski, Fuglevand, & Enoka, 1993; Tracy & Enoka, 2002) suggest they could have an increase in the ratio of COP peak-to-average velocity when compared to younger women. Moreover, given the greater limitations in limits of support in posterior movements (King et al., 1994), one would expect that discrete posterior motions would differ from anterior motions, again, disproportionately with age.

In this study, the effects of different target sizes and movement direction were assessed separately to explore their relative interaction with age. We hypothesized that in comparison to young adults, older adults would exhibit a decrease in COP movement speed and an increase in the number of compensatory submovements and ratio of peak-to-average COP velocity, particularly in posterior versus anterior movements. Thus, this study furthers the understanding of how healthy aging affects the control strategies of discrete, rapid, and accurate volitional COP movements.

2. Method

2.1. Participants

Thirteen healthy young (mean $\pm$ *SD* age 23 ± 3 years, height 164 ± 6 cm, weight 63 ± 11 kg) and twelve healthy older (age 76 ± 6 years, height 159 ± 5 cm, weight 63 ± 11 kg) women participated in this study. Both healthy young and older women had similar sized feet and body mass index (foot length 26 ± 1 cm vs. 25 ± 3 cm, body mass index 23 ± 4 kg/m² vs. 25 ± 5 kg/m², respectively). Young participants were recruited from the University of Michigan campus and older participants were recruited from a database maintained by the University of Michigan Older Americans Independence Center Human Subjects and Assessment Core. All young women filled out a medical history questionnaire and all older women underwent a medical history screening and physical examination by a nurse practitioner, in order to exclude those with significant musculoskeletal or neurological findings. All participants signed a written informed consent form approved by the University of Michigan Medical School Institutional Review Board.

2.2. Set-up

COP data was collected while participants stood on a ground-level six-channel force plate (OR6-7-1000, AMTI, Watertown, MA). Three-dimensional ground reaction forces and moments were sampled at 100 Hz. A thin wooden platform mounted on top of the force plate was used to control foot placement (i.e., stance width and anterior edge of the base of support). Real-time anteroposterior COP location was recorded using a Certus Optotrak system and First Principles software (Northern Digital, Inc., Waterloo, Canada) and calculated using the standard equation $COP_x = -M_y/F_z$. Participants viewed a COP target on a computer monitor positioned directly in front of them. In order to control for the shoe-floor interface during testing, participants wore standardized canvas shoes with a thin rubber sole that varied in 1/2 size increments between U.S. women sizes 7 1/2 to 11 1/2. Targets of varying size (2, 3, and 4 cm) were centered at two locations. One was the location during a

neutral standing posture (home target zone). The second location lay 6-cm anterior to the home target zone (anterior target zone) but well within the anterior limit of the functional base of support (FBOS), which is representative of the typical COP excursion in forward reaches in a parallel upright stance (Gillette & Abbas, 2003). A pair of horizontal lines defined the participant-specific anterior and home target zones that were used in all conditions.

2.3. Protocol

The COP movements under each participant were first measured in a neutral standing posture for 30 s in order to establish a reference point for COP target placement during testing. Participants were tested for the anteroposterior excursion of the COP during maximal sustained anterior and posterior leans in two separate 30-s trials, so as to define their FBOS. Participants then performed discrete accuracy-constrained COP movements to pseudo-randomized targets in 60-second trials on three separate laboratory test sessions. Each testing session consisted of a minimum of 6 practice trials that preceded 6 experimental trials of varying target size. In addition to submaximal trials, trials of maximal COP movement to the anterior and posterior limits of the functional base of support were used to reduce anticipation of experimental trials.

Participants were instructed to move their COP from their initial position to a target zone, after hearing a go signal consisting of a time-varying (1–3 s) auditory tone. Participants maintained their COP within the confines of an experimentally manipulated target using visual feedback from the computer monitor at a fixed magnification. Subsequent auditory cues were used to prompt a change in movement direction (Fig. 1). Participants were instructed to lean their body and move their COP ‘as fast and as accurately’ as possible, while keeping their arms crossed. Subsequent movements continued until 60 s had elapsed. On average, 21 discrete COP movements were performed on target, per trial. The first anterior and posterior movement within a trial was not analyzed, to account for re-familiarization with the task.

2.4. Data processing

Custom Matlab (v7.4, Natick, MA) data processing software routines were written to process the data. Raw force plate data were processed with a 4th order, zero-lag, low-pass Butterworth filter with a 10-Hz cutoff frequency. COP velocity and acceleration were calculated using a five-point finite difference derivative algorithm. Using an automated procedure, COP movements were extracted from each trial, using the trigger signal associated with the auditory cue to estimate the onset and offset of individual movements. COP velocity profiles were used to define the onset and offset of COP movements. The algorithm defined the onset of the COP movement by searching backward from the sample with the peak COP velocity and locating the first sample at which the velocity exceeded 10% of the maximum value ($V_{\max}$), within the starting zone (Teasdale et al., 1993). The offset of COP movement was similarly found by moving forward from the sample with the peak COP velocity and identifying the first sample less than or equal to 10% of $V_{\max}$ within the target zone.

Dependent COP variables included movement speed, number of submovements, and ratio of peak-to-average velocity. In each trial, dependent COP variables were averaged across all anterior or posterior movements for use in further analysis. For each individual COP movement: COP movement speed was defined as the movement amplitude divided by the movement time (i.e., the elapsed time from the onset to the offset); submovements were defined as pairs of zero crossings in COP acceleration after $V_{\max}$; and the ratio of peak-to-average COP velocity was defined as $V_{\max}$ divided by the average COP velocity. In

addition, to verify the expected changes in accuracy-constraints, the effective target size was measured. As previously described, the effective target size was defined as the length that would accommodate 95% of all COP endpoints.

2.5. Statistical analysis

Assumptions of normality were confirmed using the Kolmogorov-Smirnov test for each variable. Linear mixed-models, using a restricted maximum likelihood method, were used to examine the effect of age (young versus older), movement direction (anterior versus posterior), and target size (2 versus 3 versus 4 cm). Movement direction and target size were identified as repeated effects assuming a first-order autoregressive covariance structure. The relationship between movement speed and the number of submovements was evaluated using the Pearson correlation coefficient. To evaluate learning effects, a repeated-measures analysis of variance (RM-ANOVA) was used that controlled for age and target size on an aggregate of anterior and posterior COP movements. The reliability of COP measures over the three sessions was evaluated by using intraclass correlation coefficients (ICCs). Measures were aggregated for each session and the ICC equation for a 2-way random effects model of consistency was utilized in the current study. Considering the general guidelines offered in the literature, ICC values greater than .75 are assumed to correspond to excellent reliability (Fleiss, 1996). The Geisser-Greenhouse correction to the degrees of freedom was used to report univariate test results when violations to sphericity occurred in a RM-ANOVA. Post-hoc t-tests were carried out using Hochberg's step-up method to assess the most significant age and movement direction differences. $p < .05$ was considered statistically significant. All statistical analyses were carried out in SPSS 16.0 for Windows (SPSS Inc., Chicago, IL).

3. Results

All participants demonstrated no statistically significant changes in movement speed, number of submovements, and ratio of peak-to-average COP velocity ($p > .05$) across experimental sessions, based on a RM-ANOVA. The intraclass correlation coefficient (ICC) values of COP measures in this study, which ranged from .70–.93, suggest good to excellent reliability. Thus, for ease of comparison, we considered only the results from the third and final test session for this study.

3.1. Effects of Age

Overall, older women used slower speeds and an increased number of compensatory submovements as can be seen in data from a representative 60 second trial for one young and one older participant in Fig. 2. In comparison to younger women, older women had 27% decreased COP movement speed, $F(1, 23) = 10.9$, $p < .005$, twice as many compensatory submovements, $F(1, 23) = 18.7$, $p < .001$, and had an 18% increase in the ratio of peak-to-average COP velocities, $F(1, 23) = 5.9$, $p < .05$ (Fig. 3). An interaction between age and movement direction was identified in the number of submovements, $F(1, 45) = 5.0$, $p < .05$, evidenced by disproportionate increases in submovements posteriorly in the older adults. Post-hoc tests demonstrated that the most significant age-related changes occurred in the posterior movement speed in 2-cm trials and number of posterior submovements in 4-cm trials (t -test, $p < .008$).

The correlation between COP movement speed and number of compensatory submovements suggests a similar pattern of COP control for both young and older women (Fig. 4, Pearson $r^2 = -.72$ to $-.80$). COP endpoint variability, as evaluated by the effective target size demonstrated no statistically significant differences due to age in a linear mixed model (e.g.,

mean difference in effective target size < 2 mm, $p > .05$). As expected, a decreased target size also led to a decrease in the effective target size, $F(2, 69) = 16.1$, $p < .001$.

3.2. Effects of target size

Movement speed slowed in all participants as target size was decreased, $F(2, 96) = 46.0$, $p < .001$. Older women were significantly slower than younger women across all target sizes, but age-disproportional decreases in movement speed as target size decreased did not reach statistical significance. As target size decreased, the number of submovements, $F(2, 97) = 17.7$, $p < .001$, and the ratio of peak-to-average COP velocity increased, $F(2, 96) = 27.1$, $p < .001$.

3.3. Effects of movement direction

Posterior COP movements were found to be slower than anterior movements, $F(1, 37) = 9.8$, $p < .005$. Furthermore, an increased number of compensatory submovements, $F(1, 41) = 27.1$, $p < .001$, and higher ratios of peak-to-average COP velocities, $F(1, 39) = 10.7$, $p < .005$, were seen in posterior versus anterior movements. In post-hoc tests, posterior movements were found to be significantly slower across all target sizes and found to have increased submovements in 3-cm trials ($p < .005$).

4. Discussion

The purpose of this study was to examine the effect of age, movement direction, and target size on targeted COP movements in healthy women. In doing so, we furthered the understanding of age-related changes on the control of rapid volitional movements. It was hypothesized that in comparison to young, older adults would exhibit slower COP movement speeds, and increased submovements and ratio of peak-to-average COP velocity, particularly in posterior movements. The results partly confirmed our hypothesis, as older women required more frequent submovements to maintain COP accuracy, despite moving slower than young women. Further supporting our hypothesis, is the novel finding of disproportionate increases in compensatory submovements in posteriorly directed COP movements with increased age; a finding consistent with older adults taking multiple steps more often than young adults when responding to posterior perturbations (Luchies, Alexander, Schultz, & Ashton-Miller, 1994; Schulz, Ashton-Miller, & Alexander, 2005), as both represent an increase in the use of corrective actions.

4.1. Age-related changes in COP control

Our COP movement findings are consistent with planar arm movement studies showing that movement speed decreases and the number of compensatory submovements increases with age (Goggin & Meeuwse, 1992; Ketcham et al., 2002). Considering the stochastic optimized submovement model of volitional movements (Bullock & Grossberg, 1988; Crossman & Goodeve, 1983; Meyer et al., 1988), age-related increases in neuromuscular noise (Galganski et al., 1993) would be expected to lead to decreased movement speed and increased submovements. Given the role that neuromotor noise is known to have in the production of volitional upper extremity movements (Fishbach, Roy, Bastianen, Miller, & Houk, 2005; Novak, Miller, & Houk, 2000; Schmidt et al., 1979; Smits-Engelsman et al., 2002), our findings of age-related changes in COP control are not unexpected. The present findings of increased ratios of peak-to-average COP velocities with age are also consistent with increased motor unit variability and antagonist coactivation in the submaximal force generation of older adults (Galganski et al., 1993; Roos, Rice, & Vandervoort, 1997; Tracy & Enoka, 2002).

When spatiotemporal demands were placed on rapid COP movements in this study, the age-related deficits in COP control performance, particularly in posterior movements, may be a result of decrements in energy storage capacity and motor control (Cavagna & Cittero, 1974; Grillner, 1985; Guiard, 1993). Tibialis anterior activity is required for generating posterior COP movements via dorsiflexion, while the much larger triceps surae can actively apply a moment to move the COP anteriorly. The muscle-tendon lengthening speed utilized by participants in this study may seem small, but based on a biphasic, ballistic-like control pattern of upright stance (Loram & Lakie, 2002) rapidly alternating torques can be used by participants to control an inverted pendulum. Thus, ankle plantarflexors such as the triceps surae in unison with the Achilles tendon might play a significant role in compensating for the effects of gravity while leaning anteriorly (Loram & Lakie, 2002). Furthermore, given the inverse relation between the ratio of peak-to-average velocity and energy efficiency (Nelson, 1983), increases in the ratio of peak-to average COP velocities among older adults, when compared to young, suggest a decrease in the efficiency of movements of older adults. Slow discrete movements may lead to a greater number of inflections (i.e., submovements) in older adults due to neuromuscular changes and central planning deficits (Galganski et al., 1993; Goggin & Meeuwssen, 1992). An increase in motor unit recruitment and demands for information processing in discrete movements, as suggested by decreases in efficiency, can lead to increases in neuromotor noise, and thereby to an increased number of corrective submovements (Meyer et al., 1988). The increased number of corrective submovements indicate that our older adult participants still had sufficient postural control “reserve” to vary their response despite possible decrements in sensorimotor capacities. The postural control “stressor” (i.e., target size and movement amplitude) in the present study was not challenging enough to cause a loss of balance in these healthy older women. However, if applied to a more clinically impaired older adult population, the stressor might uncover a further decline in the complexity of their postural response, consistent with the concept of impaired homeostasis with increasing frailty (Lipsitz, 2008; Manor et al., 2010).

4.2. The dependence of COP speed and accuracy on movement direction

Previous studies of COP movements in response to changes in posture had found no difference between the anterior and posterior phases of continuous movement (Danion et al., 1999; Duarte et al., 2005). However, there are two significant differences in our study that may help explain why this was not found in the present study: (1) discrete, rather than continuous, movements were used in our study, which would increase movement times and corrective responses (Smits-Engelsman et al., 2002) amenable to the effects of movement direction; and (2) the use of a target at both the mid-foot, at a neutral standing posture, and at the toes, near the anterior limit of the FBOS, which would affect the underlying postural sway characteristics in the task (Duarte and Zatsiorsky, 2002) and present unique anatomical constraints.

Discrete COP movements to target are usually made in the presence of sensory feedback (Haken, Kelso, & Bunz, 1985; Smits-Engelsman et al., 2002) and therefore may be susceptible to both changes in plantar cutaneous receptor sensitivity throughout the length of the foot and with increased age (Inglis et al., 2002; Wells, Ward, Chua, & Inglis, 2003). In particular, anteroposterior postural control of upright standing posture is significantly affected by diminished plantar cutaneous sensation (hypoesthesia) (McKeon & Hertel, 2007) and an increased dependence on distal sensory feedback has been shown with increased age (Brumagne, Cordo, & Verschueren, 2004). In addition, the increased number of submovements and decreased efficiency seen in posterior versus anterior COP movements may be due to intrinsic differences in structure between the midfoot and hallux, as foot structure has been shown to be a significant contributor to dynamic foot function (Cavanagh et al., 1997; Morag & Cavanagh, 1999). Thus, physiological and anatomical differences

along the length of the foot may partly explain the observed directional difference of COP control.

4.3. Limitations

First, a relatively modest sample size limited statistical power and the choice of female subjects means that the results may not be generalizable to men without further research. Second, despite our efforts to match groups for foot length and body mass index, older women were slightly shorter than young. This would not be expected to have biased the results significantly, as the shorter height should have led older women to have less angular inertia to overcome than young. Third, we did not control for how participants prioritized task instructions. Even though participants were instructed to place equal priority on accuracy and speed, accuracy may have been prioritized over speed in some older adults, leading to greater inter-subject variability. Fourth, the feedback involved in this experiment, using visual feedback from a computer display to help volitionally shift the COP, is artificial, hence care must be taken when extending findings to whole body movements such as stooping or reaching without COP feedback. It is a limitation that we did not evaluate more than two underfoot target positions, movements to the edge of the FBOS, or mediolateral COP movements. Future studies are required to examine the underlying mechanisms behind age-related deficits in posterior COP movement performance, and further explore whole body COP control during daily movements that present the older adult with a risk for falling, such as returning from reaching, stooping, and forward bending tasks. Lastly, while the use of lean movements simplified the postural control task it may limit the generalizability of the results to reaching movements.

5. Conclusions

Despite moving more slowly, older women needed to take more frequent submovements to achieve the same level of COP accuracy as younger women, particularly when moving posteriorly. This may provide evidence of a compensatory strategy used by older adults for preventing backward falls. However, the increased number of corrective submovements suggests one mechanism by which frailer older adults may not be able to maintain balance if hurried.

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Highlights

1. We examine the effect of age and movement direction on targeted COP movements.
2. Older women are slower and use more submovements compared to younger women.
3. Rapid posterior movements differ from anterior movements, particularly among elders.
4. Results suggest compensatory strategy that may be used for preventing backward falls.

Fig. 1.

(A) Illustration of discrete COP movement initiation using auditory cues. (B) Exemplary COP movement during movements from a target at a neutral standing posture (dashed light gray lines, home target zone) to a target with a fixed movement amplitude of 6 cm, within the anterior edge of the functional base of support (dashed dark gray lines, anterior target zone) and back (solid light gray line). (C) COP velocity trajectory illustrating the zero acceleration crossings used to define submovements. Submovements were defined as a pair of zero acceleration crossings (i.e., COP velocity peaks or troughs) between the movement's peak velocity and arrest of movement.

Fig. 2. COP position and velocity data illustrating the mean (solid line) and standard deviation (shaded area) of anterior (solid center line) and posterior (dashed center line) movements during discrete 2-cm trials, representative of young and older women. Both the anterior target (dashed dark gray lines) and target at a neutral standing posture (dashed light gray lines) are presented in plots of COP position.

Fig. 3.

Influence of target size on anterior and posterior COP movements for young and older women. Mean (SD) movement speed, number of submovements, and ratio of peak-to-average COP velocity were found to be significantly affected by movement direction and target size in linear mixed models. Age was found to have a significant effect on movement speed and submovements. * and † indicate $p < .008$ in post-hoc t -tests using Hochberg's step-up method to evaluate age and movement direction differences, respectively.

Fig. 4. Effect of age on the relationship between COP movement speed and number of compensatory submovements. Correlations between movement speed and submovements for young and older women ($r^2 = -.72$ to $-.80$) were all statistically significant ($p < .01$).