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Age-related changes in speed and accuracy during rapid targeted center of pressure movements near the posterior limit of the base of support

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Abstract

Background—Backward falls are often associated with injury, particularly among older women. An age-related increase occurs in center of pressure variability when standing and leaning. So, we hypothesized that, in comparison to young women, older women would display a disproportionate decrease of speed and accuracy in the primary center of pressure submovements as movement amplitude increases.

Methods—Ground reaction forces were recorded from thirteen healthy young and twelve older women while performing rapid, targeted, center of pressure movements of small and large amplitude in upright stance. Measures included center of pressure speed, the number of center of pressure submovements, and the incidence rate of primary center of pressure submovements undershooting the target.

Findings—In comparison to young women, older women used slower primary submovements, particularly as movement amplitude increased ($P < 0.01$). Even though older women achieved similar endpoint accuracy, they demonstrated a 2 to 5-fold increase in the incidence of primary submovement undershooting for large-amplitude movements ($P < 0.01$). Overall, posterior center of pressure movements of older women were 41% slower and exhibited 43% more secondary submovements than in young women ($P < 0.01$).

Interpretations—We conclude that the increased primary submovement undershoots and secondary center of pressure submovements in the older women reflect the use of a conservative control strategy near the posterior limit of their base of support.

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Keywords

Balance; Center of pressure submovement; Postural control; Aging

1. Introduction

Falls are among the most significant causes of mortality and serious injury in adults over 65 years of age (Riley, 1997; Rubenstein and Josephson, 2002), particularly for older women (Tinetti et al., 1995; Norton et al., 1997). Backward falls are of particular significance, as they are likely to lead to wrist fractures among older women (Nevitt and Cummings, 1993). When recovering balance from large posterior perturbations, older adults are more apt to take multiple steps than young adults (Luchies et al., 1994; Schulz et al., 2005). While leaning maximally, older adults exhibited increased center of pressure (COP) variability and reduced spatiotemporal stability margins in the anteroposterior direction, when compared to young adults (van Wegen et al., 2002). The use of more frequent and variable COP movements by older adults when maintaining balance near the anteroposterior limits of stability is undesirable, as it would present a greater risk for a loss of balance, particularly in response to large perturbations.

To prevent a loss of balance while leaning when standing bipedally, the COP must often be moved rapidly in the sagittal plane to keep the center of mass (COM) from straying beyond the functional base of support. During rapid untargeted continuous COP movements, decreases in speed have been found with increased age and fall-risk (Tucker et al., 2008; Tucker et al., 2009). Considering the speed-accuracy tradeoffs that occur when the COP is moved rapidly (Duarte and Freitas, 2005), limitations on the accuracy or maximal speed of compensatory COP movements while leaning, reaching, or bending down to the floor would be expected as we age, due to neuromuscular changes (Galganski et al., 1993; Roos et al., 1997; Tracy and Enoka, 2002). Decreases in the number of large amplitude weight transfers have been observed among older adults versus young (Prado et al., 2011). As proposed by Lafond et al., postural changes (i.e., weight transfers) can be viewed as a physiological response to reduce musculoskeletal fatigue and discomfort (Brantingham et al., 1970; Cavanagh et al., 1987; Zhang et al., 1991; Lafond et al., 2009). Given the need for somatosensory information to trigger weight transfers, a decrease in weight transfers may be indicative of impairments in the somatosensory system (Lafond et al., 2009). As it is the position and change in position of the COP that controls the center of gravity, the evaluation of COP control strategies should provide insight into the mechanisms underlying age-related changes the postural control of functional movements.

Speed-accuracy tradeoffs have been observed in a wide range of tasks (Fitts, 1954; Plamondon and Alimi, 1997; Danion et al., 1999; Duarte and Freitas, 2005). The stochastic optimized submovement model proposes the use of a ballistic, primary submovement (PSM) or a series of secondary, corrective submovements (Meyer et al., 1988). Depending on the operational demands of a task, individuals can employ low force, slow submovements to achieve a high level of accuracy or high forces so as to generate rapid movements. However, to compensate for the increased motor noise, rapid movements would necessitate an increased number of submovements to accurately reach a desired target. Thus, the underlying motor control noise is expected to directly compromise primary submovement characteristics. The optimized submovement model facilitates predictions about age-related changes in the underlying submovement structure of targeted movements, as increases in motor noise due to age (Galganski et al., 1993; Roos et al., 1997; Tracy and Enoka, 2002) would be expected to result in a higher number of corrective submovements during targeted movements.

Older adults use slower movements, than young adults, to achieve a similar level of accuracy (Salthouse, 1988; Goggin and Meeuwse, 1992; Ketcham et al., 2002; Hernandez et al., 2012). However, few data exist regarding COP speed-accuracy changes with age under challenging balance conditions, such as those that might precede a loss of balance. During undisturbed upright stance, older adults have demonstrated greater delays before deploying feedback control of COP movements (Collins et al., 1995), which is consistent with findings of increased distal muscle latency in older adults during postural perturbations (Woollacott et al., 1986). Older adults have shown a higher variability in postural responses to more challenging balance conditions (Schultz et al., 1992). Thus, we would expect older adults, who tend to have greater variability during upright stance (Pyykkö et al., 1990) and slower voluntary movements when correcting postural perturbations (Stelmach et al., 1989), to use more conservative COP movements near the limits of stability, in contrast to young. On the other hand, the use of hand support has been shown to reduce postural sway with just a light touch (Jeka and Lackner, 1994; Jeka, 1997) and would be expected to reduce age-related changes in postural control. Thus, the provision of hand support would provide us with further insight into the benefits of additional support in the COP control of large amplitude movements.

The primary goal of this study was to examine the effects of age on the speed and accuracy of PSMs in large and small posterior leaning tasks. We hypothesized that in comparison to young women, older women would display a disproportionate decrease of speed and accuracy (e.g., increased number of submovements and increased incidence of COP undershooting) in their COP PSMs, as movement amplitude increased. We expect that the analysis of COP primary and secondary submovements may better describe the extent of the increasingly conservative strategy used by older adults near the limits of the functional base of support (FBOS), a quasi-static limit of stability (King et al., 1994), to maintain safe upright stance. These data may ultimately provide insight into mechanisms underlying fall avoidance in older adults, particularly in the backward direction.

2. Method

2.1. Participants

Thirteen young and twelve older healthy, community-dwelling, women were recruited for this study. Young women were 19–29 years (mean (SD) age 23 (3) years), 155–175 cm tall (164 (6) cm), and weighted 49.1–92.7 kg (63 (11) kg). Older women were 68–84 years (76 (6) years), 150–169 cm tall (159 (5) cm), and weighted 51.4–85.9 kg (63 (11) kg). All young participants completed a medical history questionnaire and older participants were physically screened by a nurse practitioner, so as to exclude those with significant musculoskeletal or neurological findings. All participants provided written informed consent as approved by University of Michigan Medical School Institutional Review Board procedures.

2.2. Instrumentation

Participants stood on a single ground-level six-channel force plate (OR6-7-1000, AMTI, Watertown, MA, USA) with data collected at a sampling rate of 100 Hz. Kinematic data were collected using a three camera, three-dimensional, motion capture system to verify movement strategies (two Optotrak 3020 and one Optotrak Certus Camera, Northern Digital, Inc., Waterloo, Canada). Infrared light emitting diodes were placed on the right leg over the lateral malleolus, heel, fifth metatarsalphalangeal joint, femoral epicondyle; on the greater trochanter; and on the right shoulder. Kinematic data were sampled at 25 Hz. All data were recorded using the Optotrak system and First Principles software (Northern Digital, Inc., Waterloo, Canada).

2.3. Protocol

Before performing accuracy-constrained COP movements, participants performed a series of 30-s calibration trials in an upright bipedal stance on the force plate with their arms crossed over their chest. Participants first stood in a neutral standing posture to establish the 'CENTER' target zone for testing. Participants then leaned as far anteriorly or posteriorly as they could without losing their balance (i.e., fall or step) over the course of a 30-s trial. The anterior and posterior limits of the participant's COP excursion were used to determine their FBOS and set the limits of the 'ANTERIOR' and 'POSTERIOR' target zones used in testing. Participants wore standardized canvas shoes to control for the shoe-floor interface during all tests. During hand support trials, participants used the side hand grips of a walker placed around the force plate at a fixed height from the floor (approximately hip height). A thin wooden platform, outlining a fixed anterior and lateral boundary for the feet, was mounted on top of the force plate to control for foot placement (i.e., stance width and anterior edge of the base of support) among all trials. One of two different sized targets (2 and 6 cm) was set at either the posterior edge of the FBOS (POSTERIOR target zone), the anterior edge of the FBOS (ANTERIOR target zone), or at the neutral standing posture (center target zone, Fig. 1). During all trials, real-time, COP feedback was provided on a display monitor positioned directly in front of the participant. A pair of horizontal lines defined the participant-specific ANTERIOR, POSTERIOR, and CENTER target zones that were used in all conditions.

Volitional COP movements were directed towards pseudo-randomized targets on three separate laboratory test sessions. Performance measures of volitional COP movements were found to demonstrate good to excellent reliability (intraclass correlation coefficient [ICC] = 0.70–0.93). Thus, for ease of interpretation only data from the final session are presented. In this study, eight trials with a 60-s duration, corresponding to two COP movement amplitudes (small-amplitude movement from ANTERIOR to CENTER target versus large-amplitude movement from ANTERIOR to POSTERIOR target), two target sizes (2 versus 6 cm), and two hand support conditions (with versus without hand support) were analyzed. Both the COP target position and target size were randomized within all trials.

In all accuracy-constrained movements, participants were instructed to move their COP as fast and as accurately as possible. A time-varying (1–3 sec) auditory tone was used to cue the start of the movement from the ANTERIOR target zone to the desired target and back. In discrete movements with hand support, participants were instructed to hold on to the walker to maintain balance, whereas in trials without hand support, participants were instructed to lean their body, while keeping their arms crossed.

2.4. Data Processing and Analysis

Only posterior COP movements from the ANTERIOR target zone were analyzed in this study. We focused solely on posterior movements from the limits of the FBOS to investigate the more challenging postural demands relevant to the study of backward falls. The first posterior movement of each trial was not analyzed so as to provide some time for re-familiarization at the start of each task. The range of COP movement amplitudes explored in this study encompass a large range of excursions feasible in a feet-in-place balance recovery strategy.

Customized Matlab (v7.4, Natick, MA) data processing software routines were used to process the data. A fourth order, zero-lag, low-pass Butterworth filter with a 10 Hz cutoff frequency was used in processing raw force plate data. A five-point finite difference derivative algorithm was used in calculating both COP velocity and acceleration. Using an automated procedure, overall COP movements were extracted from each test trial. A

primary submovement (PSM) was defined using the maximum velocity, V_2 , and a 10% threshold of the maximum velocity, V_1 (Fig. 2). The onset time, T_{on} was defined as the first time that the COP velocity continuously exceeded V_1 before reaching the maximum velocity. Similarly, the offset time, T_{off} was defined as the first time that the COP velocity reaches V_1 after decreasing below V_2 (Fig. 2).

For the purpose of investigating discrete COP movement strategies, we calculated the movement speed and COP endpoint position of PSMs. PSM speed and COP endpoint position were calculated using the COP position at T_{on} and T_{off} . Overall movement speed was calculated by dividing the movement amplitude (e.g., effective distance between onset and offset of COP movement) by the movement time (e.g., time elapsed between onset and offset of movement). Movement speed and COP endpoint variability was evaluated using the standard deviation of all PSM and overall movements in each 60-s trial. The number of submovements was defined as the number of pairs of zero acceleration crossings in the COP trajectory, between V_{max} and the offset of the movement (Fig. 2), similar to the definition of Ketcham et al. (2002). COP endpoint position was defined as the position at the offset of movement within the target zone, relative to the nearest boundary of the target with respect to the center of the movement. Based on the COP endpoint position of a PSM, the incidence rate of undershooting (i.e., a PSM COP endpoint terminated before reaching the desired target zone) was further evaluated. For each trial, the mean movement speed and endpoint position of all PSMs and overall movements were calculated for further analysis, in addition to the mean number of submovements. Baseline postural sway at an upright stance was also measured to quantify age-related changes in balance capacity. Using the 30-s evaluation of the neutral standing posture, the root mean square (RMS) values of COP excursion were calculated.

2.5. Statistical Analysis

All statistical analyses were carried out in SPSS 16.0 for Windows (SPSS Inc., Chicago, IL). To identify age group differences, independent sample t-tests were used for all subject characteristics. Repeated-measures mixed-model analyses of variance, using a restricted maximum likelihood method, were used to examine the effect of age, hand support condition (i.e., with or without hand support), movement amplitude (i.e., small or large-amplitude movement), and target size, as well as all second-level interactions with age. The linear mixed models assumed a first-order autoregressive covariance structure. To account for multiple comparisons, post-hoc tests were carried out using Hochberg's step-up method, and $P < 0.05$ was used for statistical significance.

3. Results

Older women demonstrated no significant differences in their baseline postural sway (i.e., COP RMS error) with eyes open in an upright stance, or in the amount of body weight they supported through the use of hand support, when compared to younger women ($P > 0.05$). However, older women were shorter and had a shorter mean (SD) functional base of support (FBOS) than young women (17(2) cm versus 20(1) cm, $P < 0.05$). Table 1 presents the mean and standard deviation of primary submovement (PSM) speed, PSM COP endpoint position, number of submovements, overall movement speed, and overall COP endpoint position, organized by task condition.

3.1. Primary Submovement Characteristics

Effects of Age—Older women demonstrated slower PSMs compared to young women ($F = 21.4$, $P < 0.001$), particularly in large-amplitude movements versus small-amplitude movements ($F = 20.9$, $P < 0.001$, Fig. 3). PSM COP endpoint position tended to decrease in

older versus younger women, and a borderline interaction between age and movement amplitude was observed, but neither were statistically significant after correcting for multiple comparisons. The incidence rate of undershooting (i.e., a PSM COP endpoint terminated before reaching the desired target zone) significantly increased in older versus younger women (Pearson $\chi^2 = 17.5$, $P < 0.001$). In particular, a 2 to 5-fold increase in the incidence rate of undershooting was found in the large-amplitude movements of older women, when compared to young women.

Other Effects—Overall, PSM speeds increased in large-amplitude movements versus small-amplitude movements ($F = 106.5$, $P < 0.001$), while demonstrating a 36% decrease in COP endpoint position ($F = 81.6$, $P < 0.001$). Decreasing the target size from 6 cm to 2 cm led to decreased PSM endpoint positions ($F = 355.1$, $P < 0.001$). Furthermore, the incidence rate of undershooting was found to significantly differ due to the effect of hand support, movement amplitude, and target size (Pearson $\chi^2 = 26.5 - 363.5$, $P < 0.001$). Overall, a significant correlation between PSM and overall movement speed was found (Pearson correlation $R^2 = 0.8$). As seen in Fig. 4, PSM correlated well with overall movement speed in 6-cm trials (Linear fit, $R^2 = 0.6-0.8$), but less well in 2-cm trials as fast PSMs led to more variable overall movement speeds.

3.2. Overall Movement Characteristics

Effects of Age—Overall, the COP movements of older women were 41% slower than young women ($F = 39.7$, $P < 0.001$). The effects of age were particularly significant in large versus small-amplitude movements ($F = 29.1$, $P < 0.001$), and in hand support versus no hand support trials ($F = 11.5$, $P < 0.005$). Overall, older women had a 43% increase in the number of secondary corrective submovements, when compared to young women ($F = 12.5$, $P < 0.005$). Older women tended to terminate their COP movements 13% closer to the initial target boundary ($F = 8.0$, $P < 0.01$), when compared to young women, and particularly when undergoing large-amplitude movements ($F = 6.2$, $P < 0.05$). After controlling for multiple comparisons, changes in COP endpoint position due to age and the interaction between age and movement amplitude were not found to be statistically significant.

Other Effects—The use of hand support led to a 32% increase in the mean movement speed of targeted COP movements, when compared to trials without hand support ($F = 26.5$, $P < 0.001$). COP speeds were 62% faster in large-amplitude versus small-amplitude movements ($F = 154.5$, $P < 0.001$). Decreased target size was found to significantly decrease COP speed ($F = 22.9$, $P < 0.001$).

Overall, compensatory submovements were decreased 56% in COP movements aimed at 6-cm targets as compared to 2-cm targets ($F = 62.3$, $P < 0.001$). COP endpoint position was increased 10% in movements with hand support versus no hand support ($F = 13.1$, $P < .005$). COP endpoint positions in large-amplitude movement trials decreased 9% compared to small-amplitude movement trials ($F = 18.9$, $P < 0.001$). The mean COP endpoint position of movements to 2-cm targets laid 70% closer to the initial boundary of the target in comparison to 6-cm targets ($F = 937.3$, $P < 0.001$). Overall, COP movements were terminated near the center of all targets, at a distance of 55% from the initial target boundary for the 2-cm target, and 61% for the 6-cm target.

4. Discussion

To our knowledge, this is the first study to examine the effects of age and movement amplitude on discrete and large accuracy-constrained COP movements in upright bilateral stance. A novel finding was that primary submovement (PSM) speed was disproportionately decreased in older women when compared to young as movement amplitude increased.

Even though older women achieved similar endpoint accuracy, they demonstrated a 2 to 5-fold increase in the incidence rate of the PSM undershooting the desired target in large-amplitude movements. Consistent with earlier studies of accuracy-constrained arm movements (Salhouse, 1988; Goggin and Meeuwse, 1992; Ketcham et al., 2002) and submaximal whole-body movements (Hernandez et al., 2012), older adults were 41% slower and used 43% more secondary submovements than young women. Discrete PSM characteristics were found to be consistent across varying hand support conditions and target size constraints, indicating a potential generalizability to more realistic conditions.

4.1. Factors Underlying changes in COP speed

The mean speed of targeted COP movements demonstrated significant changes due to age, hand support, movement amplitude, and target size. Older women demonstrated difficulty in increasing speeds of their volitional COP movements near the limits of the FBOS when compared to young women. The lack of movement speed changes by older women for different balance demand conditions suggests a more conservative, error adverse strategy that is consistent with previous motor control studies (Walker et al., 1997; Ketcham et al., 2002). The decrease in mean COP speed seen in older women, in comparison to young women may be partly attributed to differences in the rate of torque development of ankle plantarflexors and dorsiflexors (Thelen et al., 1996). Furthermore, older women, when compared to young women, terminated a greater number of PSMs well before reaching the desired target. The increased incidence rate of undershooting, suggests that a greater proportion of older women's overall movements required corrective submovements, consistent with previous work (Seidler-Dobrin and Stelmach, 1998).

The use of light hand support led to faster COP movements, particularly among young women, consistent with previous findings of enhanced postural stability and stabilizing hand reaction forces with hand support (Schultz et al., 1992; Reginella et al., 1999; Maki and McIlroy, 1997; Maki et al., 2003; Bateni and Maki, 2005). The use of a walker for weight support has been associated with high demands on elbow extensors, in addition to wrist flexors and shoulder flexors and adductors (Pardo et al., 1993; Bachsmidt et al., 2001; Bateni and Maki, 2005). Due to age and gender-related changes in upper and lower extremity musculature (Frontera et al., 1991; Metter et al., 1997), older women may find themselves in trouble using handrails or bars for postural recovery.

Increasingly difficult tasks, as defined by greater movement amplitude and accuracy demands, also led to slower volitional COP movements. Increases in the magnitude of COP excursion, as seen when going from small-amplitude to large-amplitude movement trials, led to faster movements, even as movements were performed towards the anteroposterior limits of stability. Consistent with findings in continuous volitional COP movements among young adults, larger movement amplitudes lead to faster movements, irrespective of target size (Duarte and Freitas, 2005). Decreased target size was also found to significantly decrease mean COP speed as seen in previous Fitts' Law tasks (Fitts, 1954; Plamondon and Alimi, 1997; Duarte and Freitas, 2005).

4.2. Movement Accuracy

Older adults have shown a reduced capacity to propel their limbs to a designated target within the initial ballistic phase of their movements and thus utilize a greater number of corrective submovements to successfully reach a target (Darling et al., 1989; Bellgrove et al., 1998). When controlling for strategic differences, older adults can perform accuracy-constrained movements with comparable accuracy but greater hesitancy and more frequent corrective submovements (Morgan et al., 1994). Consistent with previous studies (Ketcham et al., 2002), older women used a greater number of online corrections during volitional

movements to achieve similar levels of end-point accuracy, as evaluated by their effective target size. Thus, changes due to natural aging can lead to a more complex movement control strategy when accuracy constraints are placed on COP movements.

The effective target size, mean number of submovements, and COP endpoint position of accuracy-constrained movements were all influenced by target size. The effective target size and COP endpoint position when compared to the number of secondary corrective submovements represent two different aspects of movement accuracy: endpoint accuracy versus on-line control. As seen in previous studies, increased accuracy demands led to an increased number of submovements (Ketcham et al., 2002), and also decreased effective target sizes and decreases in COP endpoint position. Furthermore, decreased target size led to the earlier termination of the COP PSM relative to desired target. Thus, when asked to place an equal priority on speed and accuracy, participants use PSMs that undershot their desired target more often when target size decreased.

Decreased balance demands (i.e., hand support or smaller movement amplitudes) also led to COP endpoint positions closer to the limits of the FBOS. Postural sway increases as a standing adult leans farther away from their comfortable upright stance (Duarte and Zatsiorsky, 2002), and thus we would expect increases in postural sway near the limits of the FBOS or in movements without hand support, which would lead to the use of larger margins of stability to account for expected changes in postural sway. This change in strategy is evidenced by the decreased PSM COP endpoints in large-amplitude movements.

4.3. Limitations

As target positions were customized for each participant, changes in outcome measures due to age and types of trial may be partly explained by individual differences in FBOS lengths and desired movement amplitudes. The limited number of movement amplitude and age interaction effects seen in this study may have been attributable to the small sample size. Given that the number of trials that can be run without fatiguing a subject is limited, we were unable to fully isolate the effects of target position or movement direction on speed-accuracy tradeoffs. Furthermore, the use of a 2-cm target size as the most challenging target, may have limited the power for this study to detect interactions between age and target size. Use of a smaller target size might have brought out differences better. Another limitation of this study is that hand support was unable to be fully quantified, as an instrumented handrail was not used to measure hand reaction forces.

5. Conclusions

The increased incidence rate of undershooting by the PSM and increased secondary submovements are indicative of an increasingly conservative strategy used by older adults near the limits of the FBOS that may explain their slower speeds during whole body movements to maintain upright balance. These data may ultimately provide insight into mechanisms underlying fall avoidance in older adults, particularly in the backward direction.

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Figure 1.

A) Illustration of participant at a neutral standing posture within a defined foot boundary. B) Illustration of experimental setup showing an exemplary posteriorly-directed COP movement from the anterior target zone (dashed black lines), to the center target zone (dashed dark gray lines) located at a neutral standing posture. The black circle on the COP trajectory represents the start of the movement, whereas the black square represents the end of the movement. Dashed light gray lines indicate the posterior target zone used in large-amplitude movements. Hatched areas indicate 6-cm targets, whereas gray shaded areas indicate 2-cm targets.

Figure 2.

Position, velocity, and acceleration of a typical COP movement, decomposed by its primary and secondary submovement. V_1 represents the threshold frequency, equivalent to 10% of the peak posterior velocity, V_{max} . Pairs of acceleration zero crossings after V_{max} represent a corrective submovement. Primary submovements are defined by the onset time, T_{on} , and the offset time, T_{off} . COP position at T_{off} and at the end of the movement were used to calculate the COP endpoint position for the primary submovement, and overall movement, respectively.

Figure 3. Mean (SD) values of A) primary submovement (PSM) speed, B) PSM COP endpoint position, and C) number of submovements during small-amplitude (S2 & S6) and large-amplitude movements (L2 & L6) to 2-cm and 6-cm targets, respectively.

Figure 4.

A) Correlations between speed of the overall movement and its primary submovement (PSM), and B) correlations between movement time and primary submovement endpoint position in 2-cm and 6-cm targets. Data for both hand support conditions are aggregated.

Table 1

Mean and standard deviation (SD) of raw dependent variables for healthy young (Y) and older (O) women, organized by task condition.

Condition		COP movement parameter, by group																							
		No Hand Support				Hand Support				Small-Amplitude Movement				Large-Amplitude Movement				2-cm Target Size				6-cm Target Size			
		Mean	(SD)			Mean	(SD)			Mean	(SD)			Mean	(SD)			Mean	(SD)			Mean	(SD)		
PSM Speed (cm/s)																									
Y	21	5	26	5	18	4	29	6	23	5	23	5	23	5	23	5	23	5	23	5	23	5	23	5	
O	14	4	15	3	12	3	16	4	15	3	14	3	14	3	14	3	14	3	14	3	14	3	14	4	
PSM COP endpoint position (cm)																									
Y	2.5	1.3	3.3	1.0	3.3	1.3	2.4	1.0	1	1.0	4	1.0	4	1.0	4	1.0	4	1.0	4	1.0	4	1.0	4	1.0	
O	2	1.4	2.7	1.1	3.4	1.3	1.4	1.3	0.8	1.2	3.7	1.3	3.7	1.3	3.7	1.3	3.7	1.3	3.7	1.3	3.7	1.3	3.7	1.4	
Number of Submovements (#)																									
Y	1.1	0.7	0.9	0.4	1.1	0.6	0.9	0.5	1.4	0.9	0.7	0.5	0.7	0.5	0.7	0.5	0.7	0.5	0.7	0.5	0.7	0.5	0.7	0.3	
O	1.5	0.8	1.4	0.8	1.4	0.9	1.6	0.8	1.9	1.1	1.1	0.8	1.1	0.8	1.1	0.8	1.1	0.8	1.1	0.8	1.1	0.8	1.1	0.7	
Movement speed (cm/s)																									
Y	14	5	19	5	12	4	21	6	15	5	18	5	18	5	18	5	18	5	18	5	18	5	18	5	
O	9	3	10	3	8	3	11	4	9	3	10	3	10	3	10	3	10	3	10	3	10	3	10	3	
COP endpoint position (cm)																									
Y	2.3	0.8	3	0.8	2.7	0.8	2.6	0.9	1.2	0.5	3.9	0.9	3.9	0.9	3.9	0.9	3.9	0.9	3.9	0.9	3.9	0.9	3.9	1.1	
O	2.2	1.0	2.5	0.8	2.7	0.9	1.9	0.9	1	0.5	3.4	0.9	3.4	0.9	3.4	0.9	3.4	0.9	3.4	0.9	3.4	0.9	3.4	1.2	

NOTE: COP = center of pressure, PSM = primary submovement.