

Running head: Age and falls-risk effects on voluntary sway

Differences in rapid initiation and termination of voluntary postural sway associated with ageing and falls-risk

Murray G. Tucker<sup>a</sup>, Justin J. Kavanagh<sup>a</sup>, Steven Morrison<sup>b</sup>, Rod S. Barrett<sup>a</sup>

<sup>a</sup>School of Physiotherapy and Exercise Science, Griffith University, Queensland, Australia

<sup>b</sup>School of Physical Therapy, Old Dominion University, Norfolk, VA, USA

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Corresponding author:

Murray G. Tucker

E-mail: [murray.tucker@griffithuni.edu.au](mailto:murray.tucker@griffithuni.edu.au)

Tel.: +61 7 5552 8920

Fax: +61 7 5552 8674

**Abstract**

This study examined differences between young adults (N=25) and healthy older adults (N=48) in reaction time and the relations between centre of pressure (COP) and centre of mass (COM) motions during rapid initiation and termination of voluntary postural sway. Older adults were divided into low and high falls-risk groups based on Physiological Profile Assessment (PPA) scores of sensorimotor function. Low falls-risk older adults had slower reaction time during anterior-posterior sway initiation and decreased COP-COM separation during anterior-posterior and medial-lateral sway initiation and anterior-posterior continuous voluntary sway compared with young adults. High falls-risk older adults had slower initiation and termination reaction times in all response directions and decreased COP-COM separation during sway initiation and continuous voluntary sway in the anterior-posterior and medial-lateral directions compared with young adults. High compared with low falls-risk older adults had slower initiation and termination reaction times in all response directions, and decreased COP-COM separation during medial-lateral continuous voluntary sway. Reaction time and COP-COM measures significantly predicted group status in discriminant models with sensitivities and specificities of 72-100%. Overall, these findings highlight important associations of age-related declines in sensorimotor function related to an increased risk of falling with slower postural reaction time and reduced postural stability.

## **Introduction**

Falls are frequent events among older people and can result in disability, fear of falling, admission into aged-care, and reduced quality of life (Hill et al., 2004). Accumulated deficits in the sensorimotor systems underlying balance are strongly predictive of falls among older adults (Lord, Menz, & Tiedemann, 2003). In particular, the normal ageing process results in progressive deterioration of the visual, vestibular and somatosensory systems, reduced speed of central processing and nerve conduction, sarcopenic reductions in muscle strength, and spatiotemporally disorganised muscular activation patterns (Horak, Shupert, & Mirka, 1989; Woollacott, 1993). These physiologic changes are often accompanied by a generalised slowing of postural responses and altered movement patterns for older adults compared with young adults (Stelmach & Worringham, 1985). The movement patterns adopted by older adults often reflect a more conservative or cautious approach to balance maintenance (Hahn & Chou, 2004; Menz, Lord, & Fitzpatrick, 2003). An objective of this study was to examine differences in the speed and stability of postural responses in groups of adults with differing ages and levels of sensorimotor and balance function.

Voluntary postural sway movements represent a convenient model for examining postural control. Not only does voluntary postural sway allow the potential to systematically manipulate the aspects of the task and to objectively quantify the motor response (Borah et al., 2007; Rose & Clark, 2000), it is also a task that is sensitive to declines in movement performance with ageing and balance impairment among older people. Age-related differences in voluntary postural sway include slower reaction time to initiate sway during the 'Limits of Stability' task (Borah et al., 2007; Liaw,

Chen, Pei, Leong, & Lau, 2009; Nitz, Choy, & Isles, 2003), increased postural sway in the non-target direction of movement (Blaszczyk, Lowe, & Hansen, 1994; Hageman, Leibowitz, & Blanke, 1995) and reduced maximum lean amplitude (Blaszczyk et al., 1994; Murray, Seireg, & Sepic, 1975). In a 12 month prospective study of 263 community-dwelling older adults, fallers were found to exhibit slower and less accurate voluntary postural sway movements compared with non-fallers (Delbaere, Crombez, Van Den Noortgate, Willems, & Cambier, 2006). Furthermore, tests of voluntary postural sway and leaning actions are significantly predictive of falls in older adults with foot problems, lower limbs arthritis, stroke, and diabetes (Lord & Fitzpatrick, 2001; Menz & Lord, 2001; Sturnieks et al., 2004). In the current study, it was of interest to build upon previous research examining age-related differences in voluntary postural sway by evaluating whether measures associated with postural sway could be used to accurately identify young adults and healthy older adults with low and high risk of falls.

During normal upright stance, postural sway in the anterior-posterior direction is regulated by the ankle dorsiflexors and plantar-flexors, whereas postural sway in the medial-lateral direction is regulated primarily by the hip abductors and adductors with smaller contribution from the ankle inverters and everters (Day, Steiger, Thompson, & Marsden, 1993; Gatev, Thomas, Kepple, & Hallett, 1999). The differing neuromuscular control processes that regulate anterior-posterior and medial-lateral postural sway have been called the ankle and hip mechanisms, respectively (Winter, Prince, Stergiou, & Powell, 1993). It was suggested that the ankle and hip mechanisms were separately and independently regulated by the postural control system because they were executed orthogonally and with very little overlap during

normal bipedal stance (Winter, 1995; Winter, Prince, Frank, Powell, & Zabjek, 1996). A consistent finding in the literature is that older adults high falls-risk have pronounced declines in their medial-lateral postural stability, which is presumably due to reduced control of the abductor/adductor muscles, reduced torque generating capacity, or different response strategies (Maki, Holliday, & Topper, 1994; Nitz et al., 2003; Rogers & Mille, 2003). Examination of the abilities of high falls-risk older adults to perform medial-lateral voluntary postural sway may therefore provide novel insights regarding medial-lateral instability. Given that most voluntary sway studies have averaged over sway directions (Borah et al., 2007) or examined only the anterior-posterior direction (Blaszczyk, Hansen, & Lowe, 1993; Liaw et al., 2009; Stelmach, Phillips, DiFabio, & Teasdale, 1989), little is currently known about whether the ability of balance impaired older adults to perform voluntary postural sway depends on the direction of movement.

The regulation of standing stability by the postural control system is characterised by postural shifts of the centre of pressure (COP) with respect to the horizontal position of the centre of mass (COM) (Winter, 1995). However, most studies examining the stability of voluntary postural sway movements have reported the excursions of the COP alone. Investigation of the underlying control processes that regulate postural stability during voluntary postural sway movements may therefore benefit from a combined interpretation of COP and COM motions (Tucker, Kavanagh, Morrison, & Barrett, 2009). One such measure is the separation distance between the COP and COM (COP-COM), which is directly proportional to horizontal acceleration of the COM (Corriveau, Hebert, Raiche, & Prince, 2004; Masani et al., 2007; Winter, 1995; Yu et al., 2008). During reactive transitions of voluntary postural sway between the

anterior-posterior and medial-lateral directions, ageing and increased falls-risk are associated with reduced COP-COM separation and a reduced capacity to accelerate the COM (Tucker et al., 2009). Walking and obstacle crossing studies have also found that older adults with balance disorders exhibit greater medial-lateral instability as identified by their greater medial-lateral COP-COM separation in the non-target direction of movement compared with matched controls (Chou, Kaufman, Walker-Rabatin, Brey, & Basford, 2004; Lee & Chou, 2006). Therefore, the measurement of COP-COM separation in the target and non-target directions during voluntary postural sway may provide insights into the decline in postural stability that occurs with the normal ageing process.

An individual's reaction time to a balance perturbation is also an important determinant of their capacity to maintain postural stability during everyday activities (Stelmach & Worringham, 1985). For example, if an effective postural response is not initiated and executed within the available response time following contact with a balance hazard, a fall may be more likely to occur. The majority of studies investigating reaction time during voluntary postural sway movements have examined age-related differences in the ability to initiate movement in a specific direction as rapidly as possible (Liaw et al., 2009; Nitz et al., 2003). A complementary ability to rapidly terminate body movement is an essential movement skill that has received much less research attention. Given the potential importance of such rapid termination responses for avoiding falls (Cao, Ashton-Miller, Schultz, & Alexander, 1998; Menant, Steele, Menz, Munro, & Lord, 2009; Tirosh & Sparrow, 2004), it was of interest in the current study to examine the abilities of young and older adults to

rapidly terminate voluntary postural sway movements in response to a suddenly presented stimulus.

The aim of this study was to determine whether the reaction time to rapidly initiate and terminate voluntary postural sway and COP-COM separation during the initiation of voluntary sway and performance of voluntary sway were significantly different between young adults, low falls-risk older adults, and high falls-risk older adults. It was also of interest to determine which combination of balance measures, sway tasks, and movement directions would best discriminate between the young adults, low falls-risk older adults and high falls-risk older adults. It was hypothesised that: (1) the high falls-risk older adults and low falls-risk older adults would exhibit slower reaction time, reduced amplitudes of anterior-posterior and medial-lateral COP-COM separation and increased non-target postural sway compared with the young adults, (2) the high falls-risk older adults would exhibit slowed reaction time, reduced medial-lateral COP-COM separation and increased non-target postural sway compared with the low falls-risk older adults, and (3) the voluntary postural sway measures assessed would accurately classify the young adults, low falls-risk older adults, and high falls-risk older adults.

## **Methods**

### *Participants*

Twenty-five young adults (age range: 19-35 years, 52% male), thirty-three low falls-risk older adults (age range: 67-84 years, 52% male) and fifteen high falls-risk older adults (age range: 65-86 years, 53% male) were recruited from Griffith University Gold Coast campus and the surrounding community. Volunteers were excluded if they reported neurological, cognitive or proprioceptive disorders and recent or recurrent history of musculoskeletal injury and/or surgery. All participants provided written informed consent prior to testing. The study was approved by the Institutional Human Research Ethics Committee and all guidelines of the Committee were followed during the experimental procedures.

### *Falls-risk assessment*

Falls-risk of all of the older adults (N = 48) and a subsample of the young adults (N = 12) was calculated with the long-form Physiological Profile Assessment (PPA) (Lord et al., 2003). Tests of vision, sensation, leg strength, reaction time, postural sway, and dynamic balance provided an overall falls-risk score that ranged from -2 (very low falls-risk) to 4 (very marked falls-risk). A falls-risk score of 1 was used to categorise older individuals as either low falls-risk ( $< 1$ ) or high falls-risk ( $\geq 1$ ) (St George, Fitzpatrick, Rogers, & Lord, 2007). The PPA has been validated on over 2,000 adults and predicts multiple faller and non-multiple faller individuals with 75% accuracy in both community and institutional settings (Lord et al., 2003).

### *Voluntary postural sway tasks*

The experimental procedures used in this study were similar to our previous studies of voluntary postural sway (Tucker, Kavanagh, Barrett, & Morrison, 2008; Tucker et al., 2009). Participants were instructed to sway primarily using their ankles with as little hip motion as possible for anterior-posterior voluntary postural sway, and to sequentially load and unload the limbs for medial-lateral voluntary postural sway (Winter, 1995; Winter et al., 1996). These anterior-posterior and medial-lateral voluntary postural sway movements were performed in separate trials. For the sway initiation task, participants were required to rapidly initiate voluntary postural sway in response to a two-choice auditory cue following a random period of quiet stance of between 5 and 10 s. ‘Forward’ or ‘backward’ cues were presented for anterior-posterior sway trials, and ‘left’ or ‘right’ cues were presented for medial-lateral sway trials. Participants were instructed to react and to move as quickly as possible in the direction indicated by the auditory cue.

Following sway initiation, participants immediately commenced continuous voluntary postural sway at their preferred frequency. In 50% of trials, a “stop” auditory cue was presented after the participant had completed a randomly selected number of continuous voluntary sway oscillations (i.e. 2.0, 2.5, 3.0, 3.5, 4.0, or 4.5 cycles). The stop cue was manually presented by the principal investigator (M.G.T.) when the participant’s body lean was visually estimated as close to neutral stance during the subsequent sway oscillation. The other 50% of trials in which a stop cue was not presented were ‘catch’ trials in which the participant swayed until they had completed 5.0 continuous voluntary postural sway oscillations. When presented with a stop cue, participants were required to terminate voluntary sway as rapidly as possible and then

return to quiet stance. The instantaneous amplitude of the COP in the direction of sway when the stop cue was presented was recorded for all termination trials.

### *Instrumentation*

COP data were collected with a multicomponent force plate (Type 9287A, Kistler Instrument Corporation). COM displacement was calculated with 3D motion analysis using 14 mm diameter retro-reflective markers that were attached according to the full body VICON Plug-in-Gait model (Oxford Metrics Group Plc.) (Figure 1a-c). Marker trajectories and force plate data were synchronised and collected using Nexus software version 1.3 (Oxford Metrics Group) at sampling frequencies of 100 and 1000 Hz, respectively. The force data was collected at 1000 Hz so that reaction times could be measured with precision of milliseconds. Participants were fitted with a light-weight harness that was secured to the roof of the laboratory via a safety line. The harness and safety line were adjusting prior to testing to ensure that voluntary postural sway movements were not restricted in any way but impact with the ground would be prevented if a fall occurred (Figure 1a-b).

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### *Experimental design*

Foot position on the force plate was standardised so that stance width was equal to 10% of the participant's height and the outward foot angle was 15° (McIlroy & Maki, 1997). Prior to testing, the position of the T10 marker was recorded during maximum

static leans in the forward and backward (anterior-posterior range), and left and right (medial-lateral range) directions. Biofeedback reference points were then implemented using Nexus software (Oxford Metrics Group) so that movement of T10 was standardised to the middle 60% of the anterior-posterior and medial-lateral ranges during testing (Tucker et al., 2009). The initiation and stop auditory cues were counterbalanced for each participant. Following two practice trials, five experimental trials were collected for each sway initiation direction (i.e., forward, backward, left, and right) for a total of 10 anterior-posterior trials and 10 medial-lateral trials. Trials in which participants responded in the incorrect direction during initiation of sway, or lost their balance and/or stepped during all sway tasks were repeated.

#### *Data analysis*

COM data were up-sampled to 1000 Hz using cubic spline interpolation, and then the COP and COM data were filtered with a 4<sup>th</sup> order, zero phase shift, band-pass Butterworth filter. For both the COP and COM signals, the cut-off frequencies of the filter were 0.1 and 10 Hz. This filter removed high frequency noise and also de-trended the COP and COM signals to ensure that their trajectories accurately reflected the anterior-posterior and medial-lateral directions of postural sway. Prior to the calculation of the dependent measures, COP and COM data were normalised for each participant using maximum COP amplitudes that were obtained from two trials of maximum dynamic voluntary anterior-posterior and medial-lateral sway. The COP, COM, and COP-COM values reported in the text are in normalised units. Data analysis was performed using Matlab version 7.6 (Release 2008a, The Mathworks Inc.).

Initiation reaction time was calculated as the period from the auditory cue until the first observable change in COP amplitude associated with sway initiation. The first observable change of COP was taken as the point where the COP amplitude exceeded two SDs of baseline which was calculated from the 3 s period immediately prior to the auditory cue (Tucker et al., 2008). The sway initiation phase was the period from the end of the initiation reaction time to the response peak of COP displacement in the direction indicated by the auditory cue. The continuous voluntary sway phase was the period from the zero-crossing of COP displacement immediately following the sway initiation phase to the zero-crossing of COP displacement immediately prior to a stop cue or the end of the trial when a stop cue was not presented. Termination reaction time was the period from the stop cue to the zero-crossing of COP velocity (i.e., change in COP direction) immediately following the cue (Buchanan & Horak, 2003).

For the initiation and continuous voluntary sway phases, root mean square (RMS) amplitude of the COP and COM was calculated using the method of Prieto et al. (1996) in the target direction of voluntary sway and also in the non-target (orthogonal) sway direction. For example, during an anterior-posterior sway trial, movement in the anterior-posterior direction is target and movement in the medial-lateral direction is non-target. RMS amplitudes were used in this study because the method provides a global measure of signal amplitude that is suitable for periods of voluntary sway. The separation distance between COP and COM trajectories (COP-COM) was obtained by subtracting the COM from the COP, and then calculating the RMS of the data. It was also of interest to determine whether the groups had the same frequency of continuous voluntary sway as this may affect COP-COM separation and the ability to rapidly terminate sway. The frequency of the COP was computed during the continuous

voluntary sway phase as the inverse of the average sway period. The average sway period was determined using auto-correlation analysis. A representative example of baseline quiet stance, initiation and termination reaction times, and the sway initiation and continuous voluntary sway phases is presented in Figure 1d.

### *Statistical analysis*

One-factor Analysis of Variance (ANOVA) was used to test for main group effects (3 levels: young adults, low falls-risk older adults, high falls-risk older adults) in general characteristics and COP measures (see Table 1) and the initiation and termination reaction times. Two-factor ANOVA including group (3 levels: young adults, low falls-risk older adults, high falls-risk older adults) and sway direction (2 levels: target, non-target) factors was used to test for differences in COP-COM separation. Planned contrasts were used to identify specific differences between groups. Type 1 error rate was reduced by setting the significance level at 0.01. Effect sizes (ES) were reported as Cohen's  $d$  (Cohen, 1988).

To develop predictive models of group status, three forward stepwise discriminant analyses were performed: (1) young adults versus low falls-risk older adults, (2) young adults versus high falls-risk older adults, and (3) low versus high falls-risk older adults. Reaction time and COP-COM variables that were identified as significantly different between the groups were used as predictor variables in the discriminant analyses. A probability to enter criterion of  $p < .15$  was used to ensure that potentially important discriminators entered each model (Constanza & Afifi, 1979). In the stepwise procedure, the variable that was the strongest discriminator between groups, as measured by the Wilks' Lambda statistic, was selected in the first

step. In subsequent steps, the variable that explained most of the remaining between-groups variance and significantly improved the model was selected. This method ensured that the variables that provided the maximum combined between-groups discrimination were selected (Klecka, 1980).

The predictive capabilities of the selected sway variables were evaluated using a generalised squared-distance classification procedure, which was adjusted for unequal group sizes (Klecka, 1980). The percentage of individuals that were correctly classified from each group (i.e., sensitivity and specificity scores) were compared to the percentage of individuals that could be correctly classified due to group size proportions (prior probability) using Z tests for binomial percentages. Positive and negative likelihood ratios were also computed which indicate the odds that an individual belongs to a particular group following a particular classification result (Deeks & Altman, 2004). Variables that were not normally distributed were log-transformed prior to discriminant analysis. Statistical analyses were performed using SAS for Windows version 9.1 (SAS Institute Inc.).

## Results

### *Group differences in general characteristics and COP measures*

Significant main group effects were detected for age, PPA score, and COP amplitudes during maximum voluntary sway and continuous voluntary sway (Table 1). The young adults were significantly younger compared with the low falls-risk older adults ( $F_{1,70} = 1518.49, p < .001, ES = 10.86$ ) and the high falls-risk older adults ( $F_{1,70} = 1138.94, p < .001, ES = 11.25$ ) and also had a lower PPA score (decreased falls-risk) compared with the low falls-risk older adults ( $F_{1,57} = 35.69, p < .001, ES = 2.38$ ) and high falls-risk older adults ( $F_{1,57} = 148.74, p < .001, ES = 6.05$ ). Low falls-risk older adults also had a lower PPA score compared with the high falls-risk older adults ( $F_{1,57} = 75.70, p < .001, ES = 2.71$ ). For the COP measures, the young adults had increased COP amplitude during medial-lateral maximum voluntary sway ( $F_{1,70} = 7.37, p < .01, ES = 0.66$ ) and anterior-posterior continuous voluntary sway ( $F_{1,70} = 8.91, p < .01, ES = 0.76$ ) compared with low falls-risk older adults. The young adults also had increased COP amplitude during anterior-posterior maximum voluntary sway ( $F_{1,70} = 9.44, p < .01, ES = 1.05$ ), medial-lateral maximum voluntary sway ( $F_{1,70} = 15.28, p < .001, ES = 1.22$ ), and anterior-posterior continuous voluntary sway ( $F_{1,70} = 8.63, p < .01, ES = 0.93$ ) compared with the high falls-risk older adults.

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### *Group differences in initiation and termination reaction times*

## Running head: Age and falls-risk effects on voluntary sway

Significant main group effects were detected in reaction times for the initiation of anterior-posterior sway ( $F_{2,70} = 16.58, p < .001$ , Figure 2a), initiation of medial-lateral sway ( $F_{2,70} = 10.76, p < .001$ , Figure 2b), termination of anterior-posterior sway ( $F_{2,70} = 11.79, p < .001$ , Figure 2c), and termination of medial-lateral sway ( $F_{2,70} = 12.20, p < .001$ , Figure 2d). High falls-risk older adults had significantly slower reaction times compared with the young adults for the initiation of anterior-posterior sway ( $F_{1,70} = 33.15, p < .001, ES = 1.73$ ), initiation of medial-lateral sway ( $F_{1,70} = 16.77, p < .001, ES = 1.55$ ), termination of anterior-posterior sway ( $F_{1,70} = 9.06, p < .01, ES = 1.35$ ), and termination of medial-lateral sway ( $F_{1,70} = 14.75, p < .001, ES = 1.56$ ). High falls-risk older adults also had significantly slower reaction times compared with the low falls-risk older adults for the initiation of anterior-posterior sway ( $F_{1,70} = 14.13, p < .001, ES = 1.00$ ), initiation of medial-lateral sway ( $F_{1,70} = 9.88, p < .01, ES = 0.86$ ), termination of anterior-posterior sway ( $F_{1,70} = 21.62, p < .001, ES = 1.37$ ), and termination of medial-lateral sway ( $F_{1,70} = 16.89, p < .001, ES = 1.32$ ). Low falls-risk older adults had significantly slower reaction time compared with the young adults for the initiation of anterior-posterior sway ( $F_{1,70} = 7.17, p < .01, ES = 1.05$ ).

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### *Group differences in COP-COM separation for sway initiation and continuous voluntary sway tasks*

Significant group-by-sway direction interactions were found for COP-COM separation during the initiation of anterior-posterior sway ( $F_{2,70} = 13.21, p < .001$ ,

Figure 3a), anterior-posterior continuous voluntary sway ( $F_{2,70} = 10.74, p < .001$ , Figure 3b), and medial-lateral continuous voluntary sway ( $F_{2,70} = 4.97, p < .01$ , Figure 3d). For the initiation of anterior-posterior sway, the young adults had greater target anterior-posterior COP-COM separation compared with the low falls-risk older adults ( $F_{1,68} = 29.36, p < .001, ES = 1.03$ ) and the high falls-risk older adults ( $F_{1,68} = 22.33, p < .001, ES = 1.30$ ). For anterior-posterior continuous voluntary sway, the young adults had greater target anterior-posterior COP-COM separation compared with the low falls-risk older adults ( $F_{1,68} = 15.42, p < .001, ES = 0.71$ ) and high falls-risk older adults ( $F_{1,68} = 30.65, p < .001, ES = 1.22$ ). For medial-lateral continuous voluntary sway, the high falls-risk older adults had reduced target medial-lateral COP-COM separation compared with the young adults ( $F_{1,68} = 13.88, p < .001, ES = 0.67$ ) and the low falls-risk older adults ( $F_{1,68} = 14.04, p < .001, ES = 0.86$ ). For the initiation of medial-lateral sway (Figure 3c), the group-by sway direction interaction was not significant, however, the planned contrasts revealed significantly reduced target medial-lateral COP-COM separation for the low falls-risk older adults ( $F_{1,68} = 7.21, p < .01, ES = 0.57$ ) and high falls-risk older adults ( $F_{1,68} = 15.31, p < .001, ES = 1.05$ ) compared with the young adults.

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### *Predictive models of group status*

A summary of the selected variables, predictive capabilities, and prior probabilities for the three discriminant analyses are displayed in Table 2. The young adults and low

falls-risk older adults were significantly discriminated by two variables that were both related to the rapid initiation of anterior-posterior sway (Wilks' Lambda = 0.72,  $p < .001$ ). Two reaction time measures and one COP-COM measure were selected as significant discriminators between the young adults and the high falls-risk older adults (Wilks' Lambda = 0.31,  $p < .001$ ). This discriminant model produced the best overall classification accuracies and likelihood ratios. Two termination reaction time measures and target medial-lateral COP-COM separation during continuous voluntary sway significantly discriminated between the low and high falls-risk older adults (Wilks' Lambda = 0.59,  $p < .001$ ). Sensitivities and specificities ranged from 72-100% and were significantly greater than their corresponding prior probabilities (all  $p$ 's  $< .01$ ).

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## **Discussion**

The objectives of this study were to determine whether reaction time and COP-COM measures associated with voluntary postural sway tasks could differentiate between groups of adults with differing age and falls-risk status, and also to determine which combination of balance measures, sway tasks and movement directions best discriminated between the groups. The main findings were that older adults with high falls-risk compared with low falls-risk had particularly slowed reaction time to terminate voluntary sway, and decreased COP-COM separation when performing voluntary sway in the medial-lateral direction. The older groups compared with the young also had higher PPA scores, slower reaction times, and reduced COP-COM separation, however the specific differences in these measures for the voluntary postural sway tasks and directions was dependent on whether the older group was high or low falls-risk. The voluntary sway measures were also effective in predicting group status, with classification accuracies ranging from 72-100%.

### *Reaction time*

The high falls-risk older adults had significantly slower reaction time to initiate and terminate voluntary postural sway compared with the young adults and low falls-risk older adults for all task conditions. These findings indicate that high falls-risk older adults with impaired sensorimotor function as measured by the PPA (Lord et al., 2003) had a corresponding reduction in the ability to respond to the reaction time stimulus during initiation and termination of voluntary postural sway in the anterior-posterior and medial-lateral directions. While it is not possible from the findings of the present study to identify how specific sub-components of the task (i.e., stimulus detection, processing of stimulus, postural response) contributed to the observed

group differences in reaction time, it is clear that the high falls-risk older adults had deficits in any one or combination of these subtasks when reacting to the auditory stimuli. Reaction time tasks requiring the initiation and termination of voluntary postural sway may therefore be a useful marker of increased falls-risk among community-dwelling older people.

Our hypothesis that low falls-risk older adults would have slower voluntary postural sway reaction times compared with young adults was only partially supported by the findings of the study. The low falls-risk older adults had reaction times that were significantly slower compared with the young adults during the initiation of anterior-posterior sway and reaction times that approached significance for the initiation of medial-lateral sway ( $p = 0.047$ ). These findings are in general agreement with previous reports that ageing slows the reaction time of multidirectional leaning movements during the Limits of Stability task (Liaw et al., 2009; Nitz et al., 2003) and during rapid transitions of voluntary postural sway (Tucker et al., 2008; Tucker et al., 2009). A result contrary to our hypothesis was that no significant differences in termination reaction time were observed between the young adults and low falls-risk older adults. We believe the main reason for this absence of significance was related to the manner by which termination reaction time was calculated. Termination reaction time was the period from the stop cue to the zero-crossing of COP velocity (i.e., change in COP direction) immediately following the cue (Buchanan & Horak, 2003). Factors with the potential to influence termination reaction time included the COP position and velocity at the time of the cue, and the amplitude of COP displacement during the reaction time period (i.e., from the stop cue to the zero-crossing of COP velocity). We performed an additional analysis to determine whether

these factors were significantly different between groups. This analysis revealed no significant differences in COP position and velocity at the time of the cue between the young adults and low falls-risk older adults (all  $p$ 's > .01). However, COP displacement during the reaction time period was significantly greater for the young adults compared with the low falls-risk older adults for termination of sway in the anterior-posterior direction (Mean  $\pm$  SD; young adults: 123  $\pm$  32 mm; low falls-risk older adults: 89  $\pm$  33 mm;  $F_{1,70} = 7.12$ ,  $p < .01$ ,  $ES = 1.06$ ) and medial-lateral direction (Mean  $\pm$  SD; young adults: 215  $\pm$  53 mm; low falls-risk older adults: 172  $\pm$  46 mm;  $F_{1,70} = 8.39$ ,  $p < .01$ ,  $ES = 0.91$ ). We therefore believe that the main reason for the lack of difference in termination reaction time between the groups was that the young adults, who were expected to have a reduced termination reaction time, displaced their COP further during the reaction time period compared with the low falls-risk older adults.

#### *COP-COM separation*

As hypothesised, the low and high falls-risk older adults had reduced COP-COM separation compared with the young adults. For the low falls-risk older adults, the reduced COP-COM separation was observed during anterior-posterior and medial-lateral sway initiation and anterior-posterior continuous voluntary sway. The high falls-risk older adults had reduced COP-COM separation compared with the young for the sway initiation and continuous sway tasks in all directions. Collectively, these findings suggest that the older groups had a reduced capacity to shift the COP with respect to the COM during voluntary postural sway movements which decreased their COP-COM separation. As participants were instructed to react as quickly as possible, the smaller COP-COM separation during sway initiation was undesirable because it

limited the acceleration of the COM in the initiation direction (Masani et al., 2007; Yu et al., 2008). Decreased COP-COM separation during continuous voluntary sway also limited the capacity to halt the trajectory of the COM at the end of a sway cycle (e.g., finish swaying forward) and reverse its direction of oscillation (e.g., begin swaying backward). These findings might indicate that the older adults had reduced postural stability during voluntary postural sway tasks due to underlying sensorimotor deficits in controlling COM motions (Corriveau et al., 2000). However, as participants were only required to sway to 60% of maximum lean amplitude, it may also be argued that the reduced COP-COM separation could represent a conservative sway strategy by the older adults aimed at reducing COM acceleration near the limits of stability (Hahn & Chou, 2004).

The findings of the study also supported the hypothesis that high falls-risk older adults would have reduced medial-lateral COP-COM separation compared with the low falls-risk older adults during medial-lateral voluntary postural sway. The reduced medial-lateral COP-COM separation for the high falls-risk older adults suggests a reduced capacity to control accelerations of the medial-lateral COM (Masani et al., 2007; Yu et al., 2008). The current findings also add to the growing literature that older adults with an increased susceptibility to falls have deficits in medial-lateral postural control as identified by altered medial-lateral COP-COM separation (Chou, Kaufman, Hahn, & Brey, 2003; Chou et al., 2004). As participants performed the medial-lateral sway movements via sequential loading and unloading of each limb, the underlying cause of these findings may be deterioration in neuromuscular control of hip abductor-adductors and/or ankle inverter-everters, or an altered lateral sway strategy (Rogers & Mille, 2003; Winter et al., 1996).

No significant differences in non-target COP-COM separation were observed between the young adults, low falls-risk older adults and high falls-risk older adults during the voluntary postural sway tasks. Contrary to our findings, greater non-target medial-lateral COP-COM separation has been previously reported for traumatic brain injury patients and older adults with balance impairments and a history of falls during level walking and obstacle crossing compared with matched controls (Chou et al., 2004; Lee & Chou, 2006). Therefore, increased non-target COP-COM separation may be more readily observed during more dynamically challenging balance tasks or in individuals with neurological disorders. The lower COP-COM separation for the non-target direction compared with the target direction indicates that all three groups successfully restricted the accelerations of the COM to the target direction of motion. The current results also demonstrate that group differences in COP-COM separation are most prominent in the target direction of sway, which is also more important from a stability perspective as the greatest threat to loss of standing balance was in the direction of voluntary sway.

#### *Prediction of group status*

The classification accuracies and likelihood ratios of the discriminant models indicated that the reaction time and COP-COM separation measures had useful predictive capacities for group status with sensitivities and specificities ranging from 72-100%. The models with the strongest associations with group status were high falls-risk older adults versus young adults (sensitivity: 100%, specificity: 88%) and high versus low falls-risk older adults (sensitivity: 73%, specificity: 88%). These results demonstrate that the high falls-risk older adults were accurately identified from

the voluntary postural sway measures assessed in this study. The elevated PPA scores of the high falls-risk older adults also suggest that their reduced capacity to perform voluntary postural sway tasks was due to sensorimotor impairment (Lord et al., 2003). The discriminant model for young adults versus low falls-risk older adults was not as strongly predictive of group status (sensitivity: 76%, specificity: 72%), presumably because of less severe declines in sensorimotor function associated with a lower risk of falling.

The strongest predictors of high versus low falls-risk status out of all the task measures assessed were the reaction times to terminate anterior-posterior and medial-lateral voluntary sway. Therefore, a prominent finding of the study is that a reduced capacity to rapidly terminate body movement is strongly associated with an increased risk of falling among community-dwelling older adults. Moreover, slower termination reaction time was found to be a stronger and more important predictor of high falls-risk compared with slower initiation reaction time. These novel findings suggest that future research should examine the abilities of high and low falls older adults to rapidly terminate voluntary body movement, especially as reaction time research on fallers and non-fallers has almost exclusively focussed on movement initiation tasks. Indications of slower termination responses by older adults compared with the young have been reported in the literature (Cao et al., 1998; Menant et al., 2009; Tirosh & Sparrow, 2004), however it is currently unclear whether a reduced capacity to terminate voluntary body movement could be a causative factor in falls.

With regards to the influence of movement direction on group differences in voluntary postural sway performance, it was found that reduced COP-COM

separation during continuous voluntary sway in the medial-lateral direction was an important predictor of high versus low falls-risk. In contrast, the best predictors of the low falls-risk older adults versus the young adults were target COP-COM separation and reaction time during rapid initiation of voluntary sway in the anterior-posterior direction. Although the low falls-risk older adults also exhibited reduced target COP-COM separation during initiation of medial-lateral sway compared with the young adults, this measure was not a significant and independent predictor of group status. High falls-risk older adults were most accurately differentiated from the young adults by reaction time and COP-COM separation task measures in both the anterior-posterior and medial-lateral sway directions. Taken together, these findings suggest that deterioration in voluntary postural sway movements was most prominent in the anterior-posterior direction for the low falls-risk older adults compared with the young adults. An extra level of reduced control was apparent in the medial-lateral direction for older adults with high risk of falling compared with low risk of falling. Given that there are separate mechanisms underlying voluntary postural sway in the anterior-posterior and medial-lateral directions (Winter et al., 1996; Winter et al., 1993), the overall group differences in voluntary postural sway performance are likely to have emerged from reduced neuromuscular control at the ankles and hips.

### *Conclusion*

The current findings demonstrate that increased age and falls-risk result in deterioration in the speed and stability of postural responses associated with voluntary postural sway movements. Most notably, the time taken to terminate voluntary postural sway was a highly specific indicator of high versus low falls-risk older adults, and therefore may be an important marker of falls-risk. The high falls-risk

older adults also had reduced separation between motions of the COP and COM in the target direction during all sway tasks compared with young adults, and during continuous medial-lateral sway compared with low falls-risk older adults. The low falls-risk older adults also had reduced target COP-COM separation compared with young adults primarily when swaying in the anterior-posterior direction. On the basis of these findings, we suggest that increasing age and falls-risk results in reduced postural stability during voluntary postural sway actions because of a reduced capacity to regulate COM motions. The overall results indicate that voluntary postural sway is a useful model for examining the mechanisms underlying declines in postural stability with ageing and increased falls-risk.

## References

- Blaszczyk, J. W., Hansen, P. D., & Lowe, D. L. (1993). Evaluation of the postural stability in man: Movement and posture interaction. *Acta Neurobiologiae Experimentalis (Wars)*, *53*, 155-160.
- Blaszczyk, J. W., Lowe, D. L., & Hansen, P. D. (1994). Ranges of postural stability and their changes in the elderly. *Gait & Posture*, *2*, 11-17.
- Borah, D., Wadhwa, S., Singh, U., Yadav, S. L., Bhattacharjee, M., & Sindhu, V. (2007). Age related changes in postural stability. *Indian Journal of Physiology and Pharmacology*, *51*, 395-404.
- Buchanan, J. J., & Horak, F. B. (2003). Voluntary control of postural equilibrium patterns. *Behavioural Brain Research*, *143*, 121-140.
- Cao, C., Ashton-Miller, J. A., Schultz, A. B., & Alexander, N. B. (1998). Effects of age, available response time and gender on ability to stop suddenly when walking. *Gait & Posture*, *8*, 103-109.
- Chou, L. S., Kaufman, K. R., Hahn, M. E., & Brey, R. H. (2003). Medio-lateral motion of the center of mass during obstacle crossing distinguishes elderly individuals with imbalance. *Gait & Posture*, *18*, 125-133.
- Chou, L. S., Kaufman, K. R., Walker-Rabatin, A. E., Brey, R. H., & Basford, J. R. (2004). Dynamic instability during obstacle crossing following traumatic brain injury. *Gait & Posture*, *20*, 245-254.
- Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Lawrence Earlbaum Associates.
- Constanza, M. C., & Afifi, A. A. (1979). Comparison of stopping rules in forward stepwise discriminant analysis. *Journal of the American Statistical Association*, *74*, 777-785.

- Corriveau, H., Hebert, R., Raiche, M., & Prince, F. (2004). Evaluation of postural stability in the elderly with stroke. *Archives of Physical Medicine and Rehabilitation*, *85*, 1095-1101.
- Corriveau, H., Prince, F., Hebert, R., Raiche, M., Tessier, D., Maheux, P., et al. (2000). Evaluation of postural stability in elderly with diabetic neuropathy. *Diabetes Care*, *23*, 1187-1191.
- Day, B. L., Steiger, M. J., Thompson, P. D., & Marsden, C. D. (1993). Effect of vision and stance width on human body motion when standing: Implications for afferent control of lateral sway. *Journal of Physiology*, *469*, 479-499.
- Deeks, J. J., & Altman, D. G. (2004). Diagnostic tests 4: Likelihood ratios. *British Medical Journal (Clinical Research Ed.)*, *329*, 168-169.
- Delbaere, K., Crombez, G., Van Den Noortgate, N., Willems, T., & Cambier, D. (2006). The risk of being fearful or fearless of falls in older people: An empirical validation. *Disability and Rehabilitation*, *28*, 751-756.
- Gatev, P., Thomas, S., Kepple, T., & Hallett, M. (1999). Feedforward ankle strategy of balance during quiet stance in adults. *Journal of Physiology*, *514*, 915-928.
- Hageman, P. A., Leibowitz, J. M., & Blanke, D. (1995). Age and gender effects on postural control measures. *Archives of Physical Medicine and Rehabilitation*, *76*, 961-965.
- Hahn, M. E., & Chou, L. S. (2004). Age-related reduction in sagittal plane center of mass motion during obstacle crossing. *Journal of Biomechanics*, *37*, 837-844.
- Hill, K., Vrantsidis, F., Haralambous, B., Fearn, M., Smith, R., Murray, K., et al. (2004). *An analysis of research on preventing falls and falls injury in older people: Community, residential care and hospital settings*. Canberra, ACT: National Ageing Research Institute.

- Horak, F. B., Shupert, C. L., & Mirka, A. (1989). Components of postural dyscontrol in the elderly: A review. *Neurobiology of Aging, 10*, 727-738.
- Klecka, W. R. (1980). *Discriminant Analysis*. Beverly Hills, CA: Sage Publications.
- Lee, H. J., & Chou, L. S. (2006). Detection of gait instability using the center of mass and center of pressure inclination angles. *Archives of Physical Medicine and Rehabilitation, 87*, 569-575.
- Liaw, M.-Y., Chen, C.-L., Pei, Y.-C., Leong, C.-P., & Lau, Y.-C. (2009). Comparison of the static and dynamic balance performance in young, middle-aged, and elderly healthy people. *Chang Gung Medical Journal, 32*, 297-304.
- Lord, S. R., & Fitzpatrick, R. C. (2001). Choice stepping reaction time: A composite measure of falls risk in older people. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences, 56*, M627-632.
- Lord, S. R., Menz, H. B., & Tiedemann, A. (2003). A physiological profile approach to falls risk assessment and prevention. *Physical Therapy, 83*, 237-252.
- Maki, B. E., Holliday, P. J., & Topper, A. K. (1994). A prospective study of postural balance and risk of falling in an ambulatory and independent elderly population. *Journal of Gerontology, 49*, M72-84.
- Masani, K., Vette, A. H., Kouzaki, M., Kanehisa, H., Fukunaga, T., & Popovic, M. R. (2007). Larger center of pressure minus center of gravity in the elderly induces larger body acceleration during quiet standing. *Neuroscience Letters, 422*, 202-206.
- McIlroy, W. E., & Maki, B. E. (1997). Preferred placement of the feet during quiet stance: development of a standardized foot placement for balance testing. *Clinical Biomechanics (Bristol, Avon), 12*, 66-70.

- Menant, J. C., Steele, J. R., Menz, H. B., Munro, B. J., & Lord, S. R. (2009). Rapid gait termination: Effects of age, walking surfaces and footwear characteristics. *Gait & Posture, 30*, 65-70.
- Menz, H. B., & Lord, S. R. (2001). The contribution of foot problems to mobility impairment and falls in community-dwelling older people. *Journal of the American Geriatrics Society, 49*, 1651-1656.
- Menz, H. B., Lord, S. R., & Fitzpatrick, R. C. (2003). Age-related differences in walking stability. *Age and Ageing, 32*, 137-142.
- Murray, M. P., Seireg, A. A., & Sepic, S. B. (1975). Normal postural stability and steadiness: Quantitative assessment. *The Journal of Bone and Joint Surgery. American Volume, 57*, 510-516.
- Nitz, J. C., Choy, N. L., & Isles, R. C. (2003). Medial-lateral postural stability in community-dwelling women over 40 years of age. *Clinical Rehabilitation, 17*, 765-767.
- Rogers, M. W., & Mille, M. L. (2003). Lateral stability and falls in older people. *Exercise and Sport Sciences Reviews, 31*, 182-187.
- Rose, D. J., & Clark, S. (2000). Can the control of bodily orientation be significantly improved in a group of older adults with a history of falls? *Journal of the American Geriatrics Society, 48*, 275-282.
- St George, R. J., Fitzpatrick, R. C., Rogers, M. W., & Lord, S. R. (2007). Choice stepping response and transfer times: Effects of age, fall risk, and secondary tasks. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences, 62*, 537-542.
- Stelmach, G. E., Phillips, J., DiFabio, R. P., & Teasdale, N. (1989). Age, functional postural reflexes, and voluntary sway. *Journal of Gerontology, 44*, B100-106.

- Stelmach, G. E., & Worringham, C. J. (1985). Sensorimotor deficits related to postural stability. Implications for falling in the elderly. *Clinics in Geriatric Medicine, 1*, 679-694.
- Sturnieks, D. L., Tiedemann, A., Chapman, K., Munro, B., Murray, S. M., & Lord, S. R. (2004). Physiological risk factors for falls in older people with lower limb arthritis. *The Journal of Rheumatology, 31*, 2272-2279.
- Tirosh, O., & Sparrow, W. A. (2004). Gait termination in young and older adults: Effects of stopping stimulus probability and stimulus delay. *Gait & Posture, 19*, 243-251.
- Tucker, M. G., Kavanagh, J. J., Barrett, R. S., & Morrison, S. (2008). Age-related differences in postural reaction time and coordination during voluntary sway movements. *Human Movement Science, 27*, 728-737.
- Tucker, M. G., Kavanagh, J. J., Morrison, S., & Barrett, R. S. (2009). Voluntary sway and rapid orthogonal transitions of voluntary sway in young adults, and low and high fall-risk older adults. *Clinical Biomechanics (Bristol, Avon), 24*, 597-605.
- Winter, D. A. (1995). Human balance and posture control during standing and walking. *Gait & Posture, 3*, 193-214.
- Winter, D. A., Prince, F., Frank, J. S., Powell, C., & Zabjek, K. F. (1996). Unified theory regarding A/P and M/L balance in quiet stance. *Journal of Neurophysiology, 75*, 2334-2343.
- Winter, D. A., Prince, F., Stergiou, P., & Powell, C. (1993). Medial-lateral and anterior-posterior motor responses associated with centre of pressure changes in quiet standing. *Neuroscience Research Communications, 12*, 141-148.

Woollacott, M. H. (1993). Age-related changes in posture and movement. *Journal of Gerontology, 48*, 56-60.

Yu, E., Abe, M., Masani, K., Kawashima, N., Eto, F., Haga, N., et al. (2008). Evaluation of postural control in quiet standing using center of mass acceleration: Comparison among the young, the elderly, and people with stroke. *Archives of Physical Medicine and Rehabilitation, 89*, 1133-1139.

## TABLES

Table 1. General characteristics and centre of pressure (COP) frequencies and amplitudes for the young adults (YA), low falls-risk older adults (LFROA), and high falls-risk older adults (HFROA).

Variable	YA (N = 25)	LFROA (N = 33)	HFROA (N = 15)	<i>F</i> , <i>p</i> value
<i>Descriptive measures</i>				
Age (years)	25 ± 4	74 ± 5 <sup>+</sup>	77 ± 5*	$F_{2,70} = 916.89, p < .001$
Height (cm)	173 ± 11	167 ± 10	165 ± 13	$F_{2,70} = 3.21, p = .046$
Mass (kg)	71 ± 15	82 ± 20	77 ± 19	$F_{2,70} = 2.69, p = .075$
PPA score	-0.6 ± 0.4 <sup>‡</sup>	0.3 ± 0.5 <sup>+</sup>	1.6 ± 0.5* <sup>†</sup>	$F_{2,57} = 77.13, p < .001$
Incorrect responses (% trials)	1.0 ± 2.0	2.0 ± 3.9	2.1 ± 4.0	$F_{2,70} = 0.87, p = .422$
Balance loss (% trials)	1.0 ± 2.5	0.3 ± 1.2	1.2 ± 2.6	$F_{2,70} = 1.37, p = .262$
<i>COP measures</i>				
AP maximum sway range (mm)	233 ± 89	194 ± 77	158 ± 30*	$F_{2,70} = 4.92, p = .010$
ML maximum sway range (mm)	394 ± 170	302 ± 116 <sup>+</sup>	230 ± 46*	$F_{2,70} = 8.16, p < .001$
AP CVS amplitude (% max sway)	82.9 ± 20.9	69.4 ± 15.7 <sup>+</sup>	66.5 ± 11.9*	$F_{2,70} = 6.00, p = .004$
ML CVS amplitude (% max sway)	72.4 ± 12.1	75.3 ± 12.4	63.5 ± 11.4	$F_{2,70} = 0.41, p = .669$
AP sway frequency (Hz)	0.31 ± 0.05	0.33 ± 0.05	0.30 ± 0.04	$F_{2,70} = 2.61, p = .085$
ML sway frequency (Hz)	0.33 ± 0.06	0.34 ± 0.05	0.30 ± 0.04	$F_{2,70} = 1.99, p = .144$

Values are means ± one standard deviation. <sup>+</sup>LFROA significantly different compared with YA,  $p < .01$ . \*HFROA significantly different compared with YA,  $p < .01$ . <sup>†</sup>HFROA significantly different compared with LFROA,  $p < .01$ . <sup>‡</sup>Physiological Profile Assessment (PPA) score for YA measured from 12 individuals. AP = anterior-posterior; ML = medial-lateral; CVS = continuous voluntary sway.

Table 2. Results of the discriminant analyses between the young adults (YA), low falls-risk older adults (LFROA) and high falls-risk older adults (HFROA).

	<b>YA vs. LFROA</b>	<b>YA vs. HFROA</b>	<b>LFROA vs. HFROA</b>
Selected variables	1. Target AP COP-COM to initiate AP sway 2. RT to initiate AP sway	1. RT to initiate AP sway 2. RT to terminate ML sway 3. Target AP COP-COM to initiate AP sway	1. RT to terminate AP sway 2. RT to terminate ML sway 3. Target ML COP-COM during ML CVS
Sensitivity	LFROA: 76%	HFROA: 100%	HFROA: 73%
Specificity	YA: 72%	YA: 88%	LFROA: 88%
LR (+)	2.71	8.33	6.05
LR (-)	0.34	0.00*	0.30
Prior probability	YA: 43% LFROA: 57%	YA: 62% HFROA: 38%	LFROA: 69% HFROA: 31%

\*High sensitivity but low negative likelihood ratio paradox.

LR(+) = Likelihood ratio positive; LR(-) = Likelihood ratio negative; RT = reaction time; CVS = continuous voluntary sway;

AP = anterior-posterior; ML = medial-lateral; COP-COM = separation distance between centre of pressure and centre of mass.

# FIGURES

Figure 1.

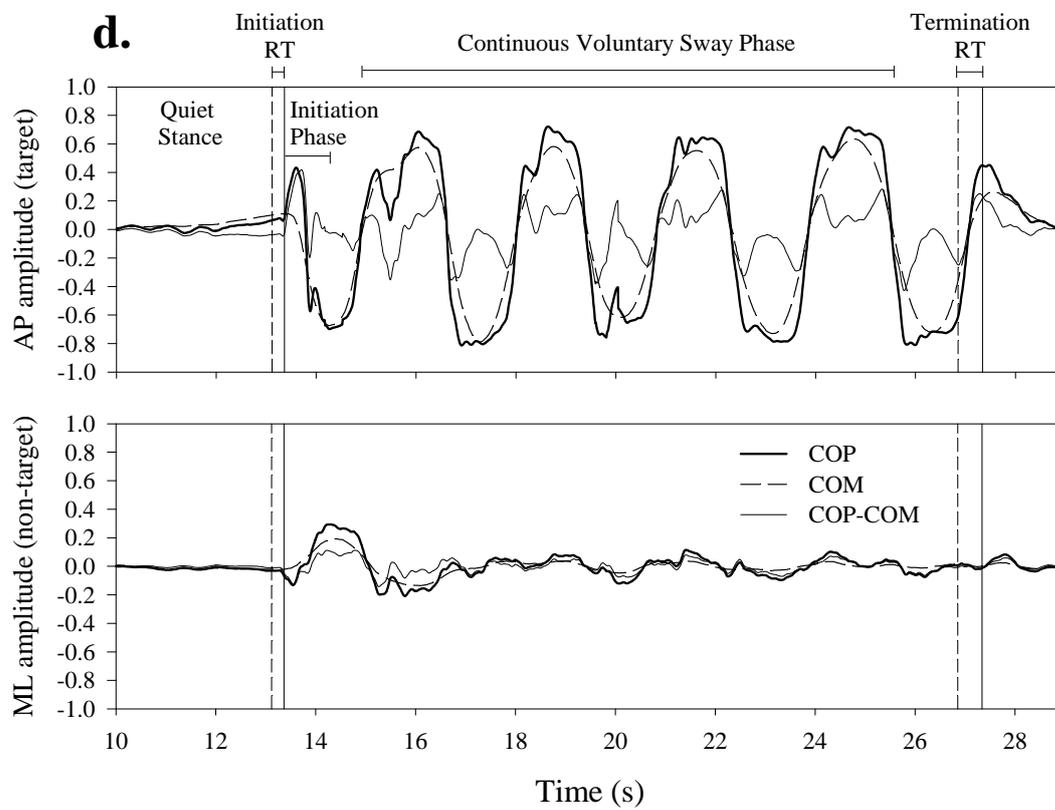
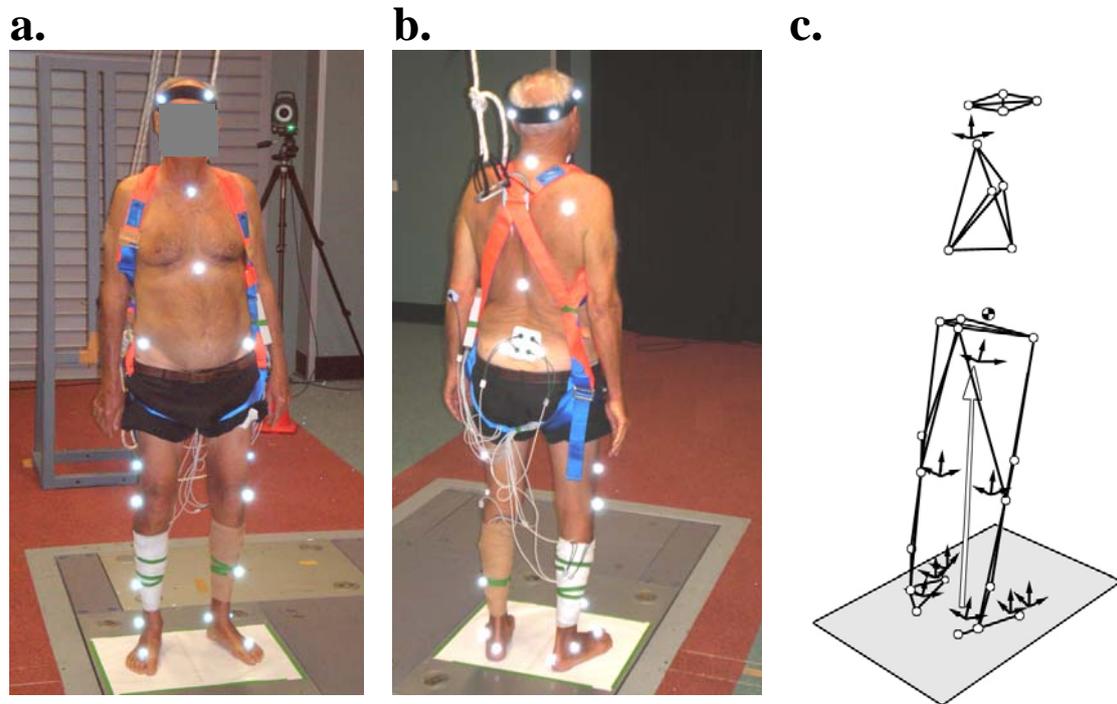


Figure 2.

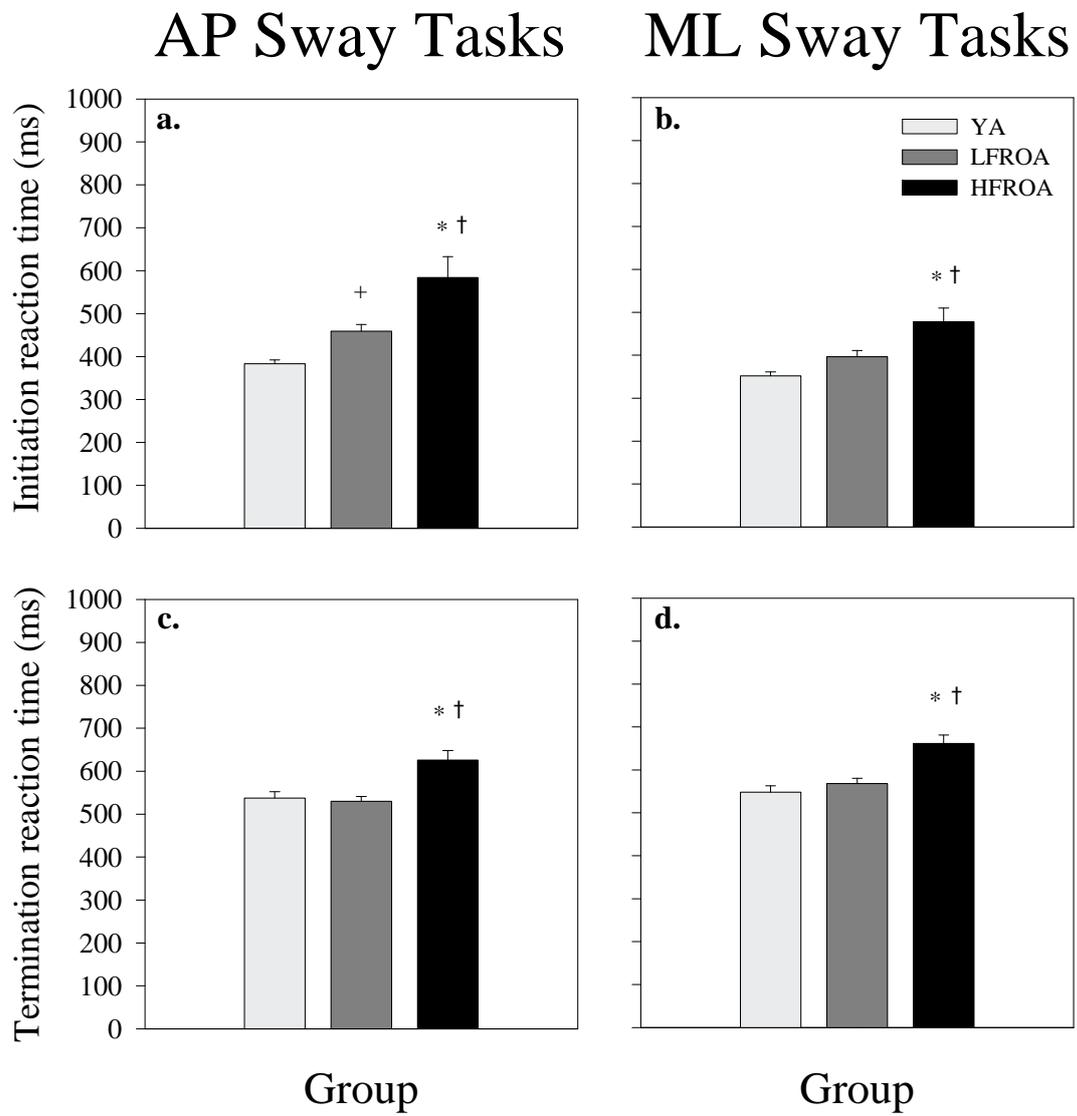
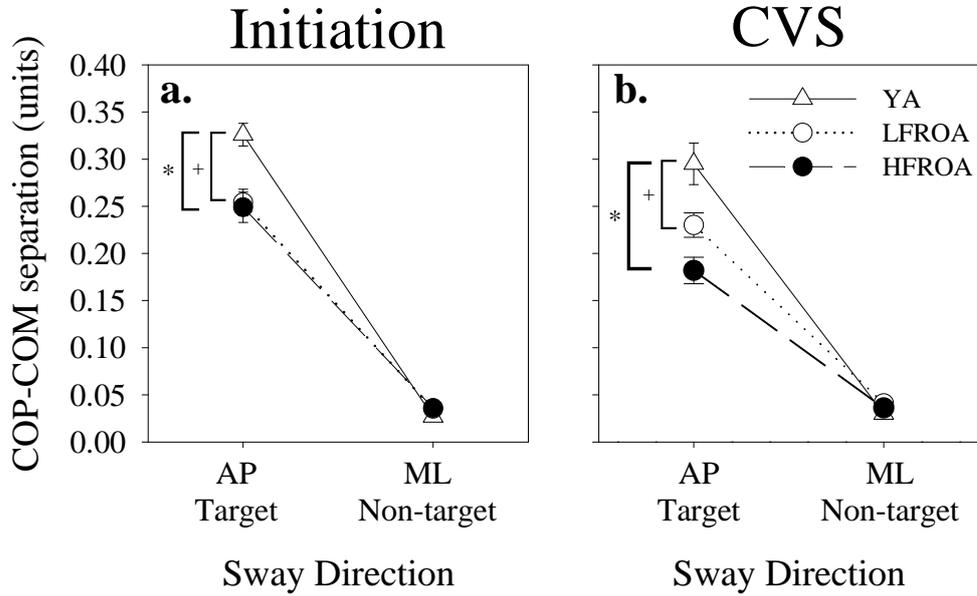
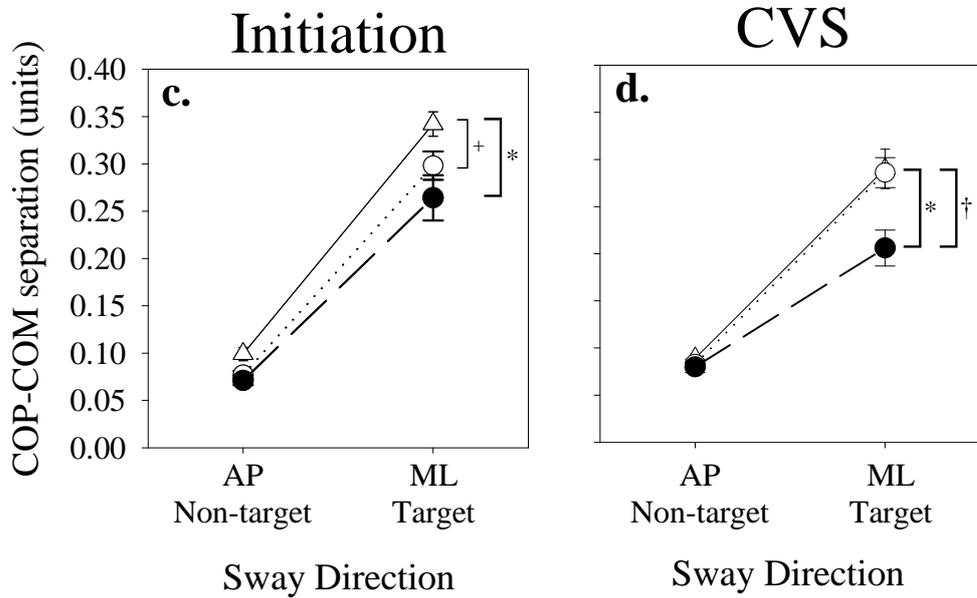


Figure 3.

## AP Sway Tasks



## ML Sway Tasks



## FIGURE CAPTIONS

Figure 1. Marker placement, biomechanical modelling, and representative data. (a-b) Anterior and posterior views of the retro-reflective marker locations, the harness and safety line, and the measured stance position on the force plate for an older adult participant. (c) VICON Plug-in-Gait model of a participant during anterior-posterior (AP) voluntary sway which shows the 3D orientation of each segment, the centre of mass (COM; shaded circle) and the vertical ground reaction force (white arrow). (d) Normalised amplitudes of the centre of pressure (COP), COM, and COP-COM separation in the target AP and non-target medial-lateral (ML) directions for a high falls-risk older adult during quiet stance, sway initiation, continuous voluntary sway and sway termination. The participant was presented with a 'backward' cue to initiate AP sway, and after a period of continuous voluntary sway, was presented a 'stop' cue to terminate AP sway. The instants of cue presentation are indicated by the dashed vertical lines and the ends of the initiation and termination reaction time (RT) periods are indicated by the solid vertical lines.

Figure 2. Reaction times of the young adults (YA), low falls-risk older adults (LFROA), and high falls-risk older adults (HFROA) during (a) initiation of anterior-posterior (AP) sway, (b) initiation of medial-lateral (ML) sway, (c) termination of AP sway, and (d) termination of ML sway. Values are mean  $\pm$  standard error. <sup>†</sup>LFROA significantly different to YA,  $p < .01$ , \*HFROA significantly different to YA,  $p < .01$ . <sup>‡</sup>HFROA significantly different to LFROA,  $p < .01$ .

Figure 3. Centre of pressure (COP) and centre of mass (COM) separation amplitudes in the target and non-target sway directions for the young adults (YA), low falls-risk

older adults (LFROA), and high falls-risk older adults (HFROA) during (a) initiation of anterior-posterior (AP) sway, (b) AP continuous voluntary sway (CVS), (c) initiation of medial-lateral (ML) sway, and (d) ML CVS. Values are mean  $\pm$  standard error in normalised units. <sup>†</sup>LFROA significantly different to YA,  $p < .01$ . \*HFROA significantly different to YA,  $p < .01$ . <sup>†</sup>HFROA significantly different to LFROA,  $p < .01$ .