# Voluntary sway and rapid orthogonal transitions of voluntary sway in young adults, and low and high fall-risk older adults.

Murray G. Tucker, BExSc (Hons), Justin J. Kavanagh, PhD, Steven Morrison, PhD,* and Rod S. Barrett, PhD

School of Physiotherapy and Exercise Science, Griffith University, Queensland, Australia

*School of Physical Therapy, Old Dominion University, Norfolk, VA, USA

Corresponding author:

Mr. Murray Tucker

School of Physiotherapy and Exercise Science

Griffith University, Gold Coast, Queensland 4222 Australia

Phone: +61 7 5552 8920, Fax: +61 7 5552 8674, Email: m.tucker@griffith.edu.au

Abstract words : 259

Text words : 4,436

Number of Figures and Tables : 5

Abbreviated Title: Effect of ageing and fall risk on voluntary sway

**Abstract**

*Background.* Falls amongst older people have been linked to reduced postural stability and slowed movement responses. The objective of this study was to examine differences in postural stability and the speed of response between young adults, and low and high fall-risk older adults during voluntary postural sway movements.

*Methods.* Twenty-five young adults (25±4 years), and thirty-two low fall-risk (74±5 years), and sixteen high fall-risk (79±7 years) older adults performed voluntary sway and rapid orthogonal transitions of voluntary sway between the anterior-posterior and medial-lateral directions. Measures included reaction and movement time and the amplitudes of the centre of pressure, centre of mass, and the separation distance between the centre of pressure and centre of mass.

*Findings.* Both fall-risk groups compared to the young had slower reaction and movement times, greater centre of pressure and/or centre of mass amplitude in the orthogonal (non-target) direction during voluntary sway, and reduced anterior-posterior and medial-lateral separation between the centre of pressure and centre of mass during voluntary sway and orthogonal transitions. High compared to low fall-risk individuals had slower reaction and movement times, increased non-target centre of mass amplitude during voluntary sway, and reduced medial-lateral centre of pressure and centre of mass separation during voluntary sway and orthogonal transitions.

*Interpretation.* Age-related deterioration of postural control resulted in slower reactive responses and reduced control of the direction of body movement during voluntary sway and orthogonal transitions. Slower postural reaction and movement time and reduced medial-lateral control of the centre of mass during voluntary sway movements are associated with increased fall-risk amongst community-living older people.

*Keywords*: reaction time; COP-COM separation; postural control; balance; ageing.

## 1. Introduction

The risk of falling increases with older age (Lord et al., 2003). Although the causes of falling among older people are multi-factorial, deterioration of balance control is a key factor (Lord et al., 2003, Horak, 2006). In the simplest context, the ability to avoid a fall involves three processes; 1) to detect a stimulus from the environment, 2) to process the information contained in the stimulus, and 3) to correctly execute the appropriate response within a critical time frame (Stelmach and Worringham, 1985, Grabiner and Enoka, 1995). Age-related degeneration of the sensory, musculoskeletal, and cognitive systems has a negative influence on the execution of these processes, which reduces the ability of older people to regulate the orientation and stability of the body during everyday tasks (Horak, 2006). In particular, the slowing of postural movements (St George et al., 2007, Lord and Fitzpatrick, 2001), decreased leg muscle strength (Pijnappels et al., 2008), and deterioration in the coordination of reactive responses to postural perturbations (Allum et al., 2002) with ageing are believed to underlie the increased susceptibility to falls amongst the elderly.

Investigations of age-related differences in postural control typically focus on movements that are performed in a single plane (Winter, 1995, Maki and McIlroy, 1996). In tasks that primarily involve anterior-posterior (AP) motion such as walking (Prince et al., 1997), obstacle crossing (Hahn and Chou, 2004), and recovering balance from a forward lean by stepping (Wojcik et al., 1999), age-related deterioration of postural control is reflected in the slower and generally less effective postural responses of older compared to younger individuals. In tasks that involve medial-lateral (ML) motion such as laterally-directed waist pulls (Mille et al., 2005), or translations of the standing surface (Maki et al., 2000), the elderly are more likely to experience inter-limb collisions and also require a greater number of steps to recover balance compared to the young. In addition, elderly fallers have pronounced ML sway during quiet stance compared to non-fallers (Maki et al., 1994, Lord et al., 1999, Delbaere et al., 2006), which is a finding that supports strong associations between deterioration of ML postural stability and increased fall-risk amongst older people (Rogers and Mille, 2003).

Given these age-related declines in whole-body movement for a single plane, a postural task that requires coordination between the AP and ML directions may be especially difficult for older people to stabilise. One simple and easy technique to investigate the effect of ageing on combined AP and ML movement is to examine postural sway in multiple directions (Hageman et al., 1995). In a previous study (Tucker et al., 2008), we assessed age-related differences in postural responses during rapid switches of voluntary sway between the AP and ML directions under choice reaction time conditions. Our results demonstrated that older individuals exhibited slower reaction time and tighter temporal coupling between centre of pressure (COP), trunk and head motion compared to the young. Although age-related differences were detected in the speed and coordination of the postural response during orthogonal sway transitions, it remains unclear how these differences influenced postural stability. In addition, because there is substantial heterogeneity of postural control among the elderly (Horak et al., 1989), it is unclear how these results generalise to sub-populations of the elderly such as those with different levels of fall-risk.

A simple method to quantify postural stability is to examine the difference between the horizontal locations of the COP and centre of mass (COM; Masani et al., 2007, Winter, 1995). Greater difference, or separation, between the COP and COM (COP-COM) increases the moment-arm between the body weight vector and the vertical ground reaction force. This in turn produces a net joint torque about the ankles or hips that accelerates the COM in the opposite direction to the COP (Winter, 1995). During quiet stance, greater COP-COM separation in the AP and ML directions has been observed with ageing (Masani et al., 2007, Berger et al., 2005), stroke (Corriveau et al., 2004) and peripheral neuropathy (Corriveau et al., 2000). Ageing and neurological impairment therefore reduce the ability to minimise horizontal accelerations of the COM in a task where less postural motion is typically associated with better performance. During more dynamic tasks such as walking and obstacle crossing, the amplitude of COP-COM separation is significantly altered with ageing (Hahn and Chou, 2004), increased fall-risk amongst older people (Lee and Chou, 2006), traumatic brain injury (Chou et al., 2004), and stroke (Said et al., 2008). Collectively, these studies suggest that COP-COM separation is sensitive to the decline in postural stability that occurs with ageing and pathology to the balance control system across a range of different postural tasks.

The purpose of this study was to examine differences between young adults, and low and high fall-risk older adults in the speed of movement, and postural stability during voluntary sway and rapid orthogonal transitions of voluntary sway between the AP and ML directions. It was hypothesised that ageing would result in slower reaction time and movement time, and altered COP-COM separation during voluntary sway and orthogonal transitions, as observed for the low and high fall-risk groups compared to the young. It was also hypothesised that similar differences in the outcome measures during voluntary sway and orthogonal transitions would be observed for the high fall-risk group compared to the low fall-risk group.

## 2. Methods

### *2.1. Participants*

Twenty-five younger (19-35 years) and forty-eight older (65-93 years) men and women participated in this study. Younger participants were recruited from the University population, and older participants were recruited from the local community by written invitation, newspaper advertisements and fliers placed within retirement villages. Older participants were required to be older than 65 years of age, and 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. The guidelines of the Institutional Human Research Ethics Committee were followed during all experimental procedures.

### *2.2. Fall-risk assessment*

Fall-risk of the older participants was calculated using the long-form Physiological Profile Assessment (PPA), which has been validated in prospective studies of falls in community and institutional settings, and predicts those at increased risk of falling with 75% accuracy (Lord et al., 2003). The long-form PPA includes tests of vision, sensation, leg muscle strength, reaction time, postural sway, and postural coordination. Scores from each of these tests were combined to provide an overall fall risk score that ranged from negative 2 (very low fall-risk) to 4 (very marked fall-risk). The older participants were divided into two groups that represented high fall-risk (≥ 1) and low fall-risk (< 1) (St George et al., 2007). The modified Baecke questionnaire and the Falls Efficacy Scale International (FES-I) were used to determine physical activity levels and the fear of falling respectively of the low and high fall-risk participants. The number of falls in the past year was also obtained from self-reports, where a fall was defined as “an event which resulted in a person coming to rest unintentionally on the ground or other lower level, not as the result of a major intrinsic event or an overwhelming hazard” (Lord et al., 1999, p1078).

*2.3 Instrumentation*

Reflective markers (14 mm) were placed on participants according to the full-body VICON Plug-In Gait model (Oxford Metrics Group Plc., West Way, Oxford, UK). During testing, participants stood on a multicomponent force plate (Type 9287A, Kistler Instrument Corporation, Amherst, NY, USA), which was surrounded by eight VICON MX-13 infrared cameras for 3D motion capture (Oxford Metrics Group). Force plate and 3D kinematic data were synchronised and collected using Nexus software v1.3 (Oxford Metrics Group) with a sampling frequency of 100 Hz for marker trajectories and 1000 Hz for ground reaction force data. To prevent injuries resulting from falls, participants wore a light-weight safety harness during testing which was secured to the roof of the laboratory using a pulley system. The harness and pulley system were adjusted for each participant prior to testing to ensure that their voluntary sway movements were not restricted.

*2.4. Task and experimental design*

Foot position was traced onto sheets of paper that were affixed to the force plate. Stance width was standardised to 10% of the participant’s height with an outward foot angle of 15 degrees (McIlroy and Maki, 1997). Participants matched their measured foot position to their footprints prior to the commencement of each trial. During testing, participants executed rapid, orthogonal transitions of voluntary postural sway between the AP and ML directions in response to a two-choice auditory cue (for greater details see Tucker et al., 2008). For AP-ML transitions, participants initially swayed in the AP direction and then reacted to a 'left' or 'right' auditory cue. After reacting left or right, participants commenced and continued ML sway. For ML-AP transitions, participants initially swayed in the ML direction and then reacted to a 'forward' or 'backward' auditory cue. After reacting forward or backward, participants commenced and continued AP sway.

Auditory cues were presented to participants at approximately their neutral stance position after they had completed 2.0, 2.5, 3.0, 3.5, 4.0, or 4.5 oscillations of voluntary sway. The COP amplitude in the direction of sway at cue onset was not significantly different between groups (*P's* > .05). The number of oscillations prior to cue onset was randomised, and the sequence of auditory cue presentation was counterbalanced for each participant. All participants were instructed to react and to move as quickly as possible in the direction indicated by the auditory cue. Participants were also instructed to restrict motion to the ankle joint for AP sway, and to sequentially load and unload each leg for ML sway, and for all sway movements, to keep the arms relaxed alongside the trunk and refrain from lifting the feet off the ground. Following one practice trial, five experimental trials were collected for each direction of response (i.e. forward, backward, left, and right), with a minimum of three trials per direction suitable for subsequent analysis. All participants were provided with 30 s rest intervals in-between trials, and were given seated breaks as required. Trials in which the participant responded in the wrong direction, lost their balance and/or stepped were recorded.

The amplitude of voluntary sway was standardised during the AP-ML and ML-AP sway tasks by on-line monitoring of a marker placed over the tenth thoracic spinous process (T10). Prior to testing, T10 position was recorded during maximum static leans performed forward and backward (AP range), and left and right (ML range). Nexus software (Oxford Metrics Group) was then used to implement T10 biofeedback reference points that permitted sway within the middle 60% of the AP and ML ranges. When the real-time T10 position exceeded the reference point during voluntary sway, an auditory beep indicated the need to reverse the current direction of oscillation. During testing, all participants swayed within their designated AP and ML ranges at their preferred frequency. These frequencies were not significantly different between groups for pre- or post-transition sway (*P's* > .05).

*2.5. Dependent measures*

*2.5.1. Speed of movement related variables and phases of the task*

Reaction time to the auditory cue was determined from the COP of the post-transition sway direction (e.g. ML COP for AP-ML transitions) using the algorithm of Mills et al. (2007). A 20 ms sliding window moved forwards from the auditory cue at 1 ms intervals until all data points within the sliding window exceeded a threshold. The threshold was the average amplitude of the COP 100 ms immediately prior to the auditory cue, plus or minus two standard deviations of non-target COP data computed during two voluntary sway oscillations prior to the cue. Movement time was calculated from the end of reaction time to the first COP peak of voluntary sway in the direction indicated by the auditory cue. The raw amplitude of this first COP peak was recorded. The transition phase was defined as the movement time period. The pre- and post-transition phases were two complete oscillations of voluntary sway, which were immediately prior to the cue for the pre-transition phase, or immediately following the transition for the post-transition phase (see Figure 1). The COP, COM, and COP-COM dependent measures were calculated from the pre-transition, transition, and post-transition phases.

*2.5.2. COP and COM related variables*

The COM was computed from the weighted sum of the centres of mass of the modelled body segments, which were obtained using the full-body VICON Plug-In Gait model. Subsequent data analysis was performed using custom designed software in Matlab v7.1 (Release 14, The Mathworks Inc., Natick, MA, USA). COM data was up-sampled to 1000 Hz, and then all data filtered with a $4^{th}$ order, zero-phased, band-pass Butterworth filter with cut-off frequencies at 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 AP and ML directions of body sway. COP and COM data were then normalised to the maximum (forward and right), and minimum (backward and left) COP amplitudes that were obtained from two trials of maximum voluntary AP and ML sway (see Table 1 for maximum COP amplitudes). For each phase of the task, root mean square (RMS) amplitude was calculated for the COP and COM in the target sway direction, and also in the non-target (orthogonal) direction. The separation difference between the COP and COM trajectories was also obtained by subtracting the COM from the COP, and then calculating the RMS of the data (COP-COM) in the target and non-target directions.

### *2.6. Statistical analysis*

One-factor repeated measures Analysis of Variance (ANOVA), and Analysis of Covariance (ANCOVA) were used to detect main group effects (3 levels: young, low fall-risk, high fall-risk) for the AP-ML and ML-AP sway tasks separately. ANOVA was used to test for group differences in general characteristics and the pre- and post-transition variables. ANCOVA was used to test for group differences in the transition variables. The covariates for this analysis were the pre-transition variables that were significantly different between groups and COP amplitude in the direction of sway at cue onset. In the event of a significant main group effect, *posteriori* contrasts were used to compare individual means. All statistical analyses were performed using custom software developed in SAS for Windows v9.1 (SAS Institute Inc., Cary, NC, USA), with significance accepted at $P < .05$.

## 3. Results

### *3.1. Group characteristics*

A significant main effect was detected between groups for age, PPA score, and maximum COP amplitude in the forward, left, and right directions (Table 1). The high fall-risk group was older and had a higher PPA score (increased fall-risk) compared to the low fall-risk group ($P$’s $< .01$). The low and high fall-risk groups had reduced forward, left and right COP amplitude compared to the young during maximum voluntary sway ($P$’s $< .05$).

\-----------------------------------------------

Insert Table 1 about here

\-----------------------------------------------

### *3.2. Representative data*

Representative time-series plots of COP, COM and COP-COM data, and AP versus ML COP plots for an ML-AP trial for young, low fall-risk, and high fall-risk participants are displayed in Figure 1. Following cue onset, there was a delay in movement initiation prior to the reaction response. The reaction response was characterised by an initial peak of the COP with respect to the COM, which was followed by oscillations in the post-transition direction and diminished oscillation in the pre-transition direction. COP and COM excursions appeared smaller and more visually irregular in the non-target direction compared to the target direction of sway.

-----------------------------------------------

Insert Figure 1 about here

-----------------------------------------------

*3.3. AP-ML task*

*3.3.1. Pre-transition variables*

A significant main effect was detected between groups for AP COP (F = 5.28, $P < .01$), and ML COP amplitudes (F = 6.03, $P < .01$). The low and high fall-risk groups had reduced AP COP and increased ML COP amplitudes compared to the young (*P*'s < .01) (Figure 2a).

-----------------------------------------------

Insert Figure 2 about here

-----------------------------------------------

*3.3.2. Transition variables*

A significant main effect was detected between groups for reaction time (F = 8.90, $P < .001$), movement time (F = 3.69, $P < .05$), peak raw COP amplitude at the end of movement time (F = 12.66, $P < .001$), and the AP COP (F = 7.29, $P < .01$), AP COP-COM (F = 6.71, $P < .01$), and ML COP-COM amplitudes (F = 3.58, $P < .05$). Reaction time and movement time were slower for the low and high fall-risk groups compared to the young, and the high fall-risk group had slower reaction time compared to the low fall-risk group (*P*'s < .05) (Figures 3a, and 3c). Peak raw COP amplitude was reduced for the low and high fall-risk groups compared to the young, and for the high fall-risk group compared to the low fall-risk group (*P*'s < .05) (mean ± SD; young: 139 ± 31 mm; low fall-risk: 126 ± 29 mm; high fall-risk: 106 ± 21 mm). The low and high fall-risk groups also had reduced AP COP and AP COP-COM amplitudes compared to the young, and the high fall-risk group had reduced ML COP-COM amplitude compared to the young and low-fall-risk groups (*P*'s < .05) (Figures 2b, and 2h).

-----------------------------------------------

Insert Figure 3 about here

-----------------------------------------------

*3.3.3. Post-transition variables*

A significant main effect was detected between groups for AP COM (F = 7.11, *P* < .01) and ML COP-COM amplitudes (F = 3.80, *P* < .05). The high fall-risk group had increased AP COM amplitude and reduced ML COP-COM separation compared to the young and low fall-risk groups (*P*'s < .01) (Figures 2f, and 2i).

*3.4. ML-AP task*

*3.4.1. Pre-transition variables*

A significant main effect was detected between groups for AP COM (F = 10.01, *P* < .001), ML COM (F = 4.28, *P* < .05), and ML COP-COM amplitudes (F = 3.42, *P* < .05). The low fall-risk group had greater AP COM amplitude compared to the young (*P* < .05) (Figure 4d). The high fall-risk group had increased AP COM and ML COM amplitudes compared to the young and low fall-risk groups, and reduced ML COP-COM separation compared to the low fall-risk group ($P$'s < .05) (Figures 4d, and 4g).

-------------------------------------------------

Insert Figure 4 about here

-------------------------------------------------

*3.4.2. Transition variables*

A significant main effect was detected between groups for reaction time (F = 24.13, $P$ < .001), movement time (F = 4.82, $P$ < .05), peak raw COP amplitude at the end of movement time (F = 6.92, $P$ < .01), and the AP COP (F = 6.98, $P$ < .01), AP COM (F = 3.96, $P$ < .05), and ML COP-COM amplitudes (F = 11.83, $P$ < .001). Reaction time was slower for the low and high fall-risk groups compared to the young, and the high fall-risk group compared to the low fall-risk group ($P$'s < .05) (Figure 3b). The high fall-risk group also had slower movement time compared to the young and low fall-risk groups ($P$'s < .05) (Figure 3d). Peak raw COP amplitude was reduced for the low and high fall-risk groups compared to the young ($P$'s < .05) (mean ± SD; young: 85 ± 18 mm; low fall-risk: 76 ± 20 mm; high fall-risk: 68 ± 18 mm). Compared to the young group, the low fall-risk group also had reduced AP COM amplitude, and the low and high fall-risk groups had reduced AP COP amplitude and ML COP-COM separation ($P$'s < .05) (Figures 4e, 4b, and 4h).

*3.4.3. Post-transition variables*

A significant main effect was detected between groups for AP COP ($F = 5.06$, $P < .01$), ML COP ($F = 3.50$, $P < .05$), ML COM ($F = 14.37$, $P < .001$), and ML COP-COM amplitudes ($F = 3.93$, $P < .05$). The low and high-fall risk groups had reduced AP COP amplitude compared to the young ($P$'s $< .05$) (Figure 4c). The low fall-risk group also had increased ML COP, ML COM and ML COP-COM amplitudes compared to the young ($P$'s $< .05$) (Figures 4c, 4f, and 4i). The high fall-risk group had increased ML COM amplitude compared to the young and low-fall-risk groups ($P < .05$) (Figure 4f).

## 4. Discussion

### *4.1. Voluntary sway in the young, low fall-risk and high fall-risk groups*

The low and high fall-risk groups compared to the young exhibited reduced COP amplitude in the forward and sideways directions during maximum voluntary sway and reduced target AP COP amplitude during voluntary sway and orthogonal transitions. These findings indicate that older people have a reduced ability to shift the body maximally within the base of support, and also to control voluntary sway via AP shifts of the COP. Age-related reduction in COP amplitude during voluntary sway movements may be due to reduced leg muscle strength, impaired perception of stability boundaries, or an attempt to increase the margin of postural stability (Blaszczyk et al., 1993, Blaszczyk et al., 1994). In agreement with our hypothesis, the high fall-risk group generally exhibited reduced target ML COP-COM separation compared to the young and low fall-risk groups during ML voluntary sway and orthogonal transitions. The high fall-risk group therefore had a closer ML alignment between the COP and COM, which although stable under static conditions, would not facilitate postural stability during voluntary sway as the ability to generate a stabilising torque and accelerate the COM in the desired direction is reduced (Winter, 1995).

Increased sway in the non-target direction was exhibited by the low and high fall-risk groups compared to the young, and the high fall-risk group compared to the low-fall risk group. The increased non-target sway for the older groups compared to the young was due to increased COP and/or COM amplitude, whereas the increased non-target sway for the older group with the higher risk of falling was exclusively due to increased COM amplitude. These results demonstrate that ageing and increased fall-risk reduce the ability to concurrently regulate AP and ML sway and to control multi-directional postural movements. Similar to the current results, increased non-target sway has been observed in older compared to younger adults (Hageman et al., 1995, Blaszczyk et al., 1994), and fallers compared to non-fallers (Delbaere et al., 2006). As ageing and increased fall-risk are associated with a reduction in the capability to detect sensory stimuli (Lord et al., 2003, Grabiner and Enoka, 1995, Stelmach and Worringham, 1985), the increased non-target sway may be a mechanism to enhance sensory feedback and improve postural stability (Patla et al., 1990). Alternatively, individuals with reduced postural control may have used more attention to stabilise the target direction of sway, which was presumably at the expense of the non-target direction (Woollacott and Shumway-Cook, 2002). The amplitude of sway in the non-target direction during voluntary postural sway may be a simple and easy test to screen older individuals for risk of falls.

*4.2. Reaction and movement times of the young, low fall-risk and high fall-risk groups during sway transitions*

The results confirmed our hypotheses that ageing and increased fall-risk would result in slower reaction and movement responses during rapid orthogonal transitions of voluntary sway. The slower responses of the older groups compared to the young also supports the results of our previous study involving younger and older men (Tucker et al., 2008). In addition, the groups with slower movement time also had reduced raw amplitude of their COP responses to the auditory cue. Therefore the slowing of movement time with ageing and increased fall-risk occurred over shorter distances of COP displacement. Given the importance of being able to respond quickly to unexpected stimuli to avoid falls, the negative influence of aging and increased fall-risk to slow reaction and movement responses is important clinically (Grabiner and Enoka, 1995, Stelmach and Worringham, 1985). Slower reaction time and movement time for high compared to low fall-risk individuals has been observed during voluntary stepping tasks that challenge whole-body stability (Lord and Fitzpatrick, 2001, St George et al., 2007), which together with the findings of the present study, suggest that the speed of postural responses are an important determinant of fall-risk in older people.

### *4.3. Postural stability in the young, low fall-risk and high fall-risk groups during sway transitions*

In agreement with our hypothesis, the low and high fall-risk groups generally exhibited reduced AP and ML COP-COM separation compared to the young during orthogonal transitions. Therefore the older groups had a reduced ability to accelerate the COM in the desired direction during the transition phase compared to the young. The primary mechanism underlying the greater AP COP-COM separation for the young compared to the older groups was increased AP COP amplitude. Also in agreement with our hypothesis, the high fall-risk group had decreased ML COP-COM separation during AP-ML transitions compared to the low fall-risk group. Considering that previous studies have also shown that individuals with reduced postural stability exhibit altered COP-COM separation in the ML direction (Chou et al., 2004, Lee and Chou, 2006), there is growing evidence that measures of ML COP-COM separation may be useful in differentiating between individuals with low and high fall-risk.

*4.4. Medial-lateral postural stability in the young, low fall-risk and high fall-risk groups during voluntary sway and orthogonal transitions*

One prominent result of this study concerned the generalised effect of ageing and increased fall-risk on the control of ML postural stability. Following ML-AP transitions, the low fall-risk group compared to the young had increased non-target ML COP and COM and COP-COM amplitudes. These results suggest that the low fall-risk group compared to the young experienced difficulty to suppress their pre-transition ML voluntary sway during the post-transition phase. In addition, 5 out of the 7 significant differences between the high and low fall-risk groups for the COP, COM, and COP-COM variables were related to the ML direction. The greater target and non-target ML COM amplitude of the high-fall risk group compared to the low fall-risk group suggests they had poor control of their ML COM trajectory which reduced their ML COP-COM separation during voluntary sway and orthogonal transitions. Collectively, these results suggest that deterioration of postural control with ageing and increased fall-risk may be pronounced in the ML direction during voluntary postural sway movements. In support of our findings, particular declines in the control of ML postural stability with increased fall-risk have been reported for standing postural sway (Delbaere et al., 2006, Lord et al., 1999, Maki et al., 1994).

## 5. Conclusions

The overall findings of the present study indicate that older adults with increased susceptibility to falling have slowed postural reaction and movement times, and reduced control of their COM. The association between the PPA classifications of fall-risk with speed of response, non-target postural sway and the amplitude of COP-COM separation indicates that the current protocol of voluntary sway and orthogonal transitions of voluntary sway may be useful to define the fall-risk of community-living older people.

**References**


Allum, J.H., Carpenter, M.G., Honegger, F., Adkin, A.L., Bloem, B.R., 2002. Age-dependent variations in the directional sensitivity of balance corrections and compensatory arm movements in man. J Physiol. 542, 643-663.

Berger, L., Chuzel, M., Buisson, G., Rougier, P., 2005. Undisturbed upright stance control in the elderly: Part 1. Age-related changes in undisturbed upright stance control. J Mot Behav. 37, 348-358.

Blaszczyk, J.W., Hansen, P.D., Lowe, D.L., 1993. Postural sway and perception of the upright stance stability borders. Perception. 22, 1333-1341.

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.

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.

Corriveau, H., Hebert, R., Raiche, M., Prince, F., 2004. Evaluation of postural stability in the elderly with stroke. Arch Phys Med Rehabil. 85, 1095-1101.

Corriveau, H., Prince, F., Hebert, R., Raiche, M., Tessier, D., Maheux, P., Ardilouze, J.L., 2000. Evaluation of postural stability in elderly with diabetic neuropathy. Diabetes Care. 23, 1187-1191.

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. Disabil Rehabil. 28, 751-756.

Grabiner, M.D., Enoka, R.M., 1995. Changes in movement capabilities with aging. Exerc Sport Sci Rev. 23, 65-104.

Hageman, P.A., Leibowitz, J.M., Blanke, D., 1995. Age and gender effects on postural control measures. Arch Phys Med Rehabil. 76, 961-965.

Hahn, M.E., Chou, L.S., 2004. Age-related reduction in sagittal plane center of mass motion during obstacle crossing. J Biomech. 37, 837-844.

Horak, F.B., 2006. Postural orientation and equilibrium: What do we need to know about neural control of balance to prevent falls? Age Ageing. 35 Suppl 2, ii7-ii11.

Horak, F.B., Shupert, C.L., Mirka, A., 1989. Components of postural dyscontrol in the elderly: A review. Neurobiol Aging. 10, 727-738.

Lee, H.J., Chou, L.S., 2006. Detection of gait instability using the center of mass and center of pressure inclination angles. Arch Phys Med Rehabil. 87, 569-575.

Lord, S.R., Fitzpatrick, R.C., 2001. Choice stepping reaction time: A composite measure of falls risk in older people. J Gerontol A Biol Sci Med Sci. 56, M627-632.

Lord, S.R., Menz, H.B., Tiedemann, A., 2003. A physiological profile approach to falls risk assessment and prevention. Phys Ther. 83, 237-252.

Lord, S.R., Rogers, M.W., Howland, A., Fitzpatrick, R., 1999. Lateral stability, sensorimotor function and falls in older people. J Am Geriatr Soc. 47, 1077-1081.

Maki, B.E., Edmondstone, M.A., Mcilroy, W.E., 2000. Age-related differences in laterally directed compensatory stepping behavior. J Gerontol A Biol Sci Med Sci. 55, M270-277.

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. J Gerontol. 49, M72-84.

Maki, B.E., Mcilroy, W.E., 1996. Postural control in the older adult. Clin Geriatr Med. 12, 635-658.

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. Neurosci Lett. 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. Clin Biomech (Bristol, Avon). 12, 66-70.

Mille, M.L., Johnson, M.E., Martinez, K.M., Rogers, M.W., 2005. Age-dependent differences in lateral balance recovery through protective stepping. Clin Biomech (Bristol, Avon). 20, 607-616.

Mills, P.M., Barrett, R.S., Morrison, S., 2007. Agreement between footswitch and ground reaction force techniques for identifying gait events: Inter-session repeatability and the effect of walking speed. Gait Posture. 26, 323-326.

Patla, A.E., Winter, D.A., Frank, J.S., Walt, S.E., Prasad, S. (1990) Identification of age-related changes in the balance-control system. IN Duncan, P.W. (Ed.) Balance: Proceedings of the apta forum. Alexandria, VA, APTA.

Pijnappels, M., Van Der Burg, P.J., Reeves, N.D., Van Dieen, J.H., 2008. Identification of elderly fallers by muscle strength measures. Eur J Appl Physiol. 102, 585-592.

Prince, F., Corriveau, H., Hebert, R., Winter, D.A., 1997. Gait in the elderly. Gait Posture. 5, 128-135.

Rogers, M.W., Mille, M.L., 2003. Lateral stability and falls in older people. Exerc Sport Sci Rev. 31, 182-187.

Said, C.M., Goldie, P.A., Patla, A.E., Culham, E., Sparrow, W.A., Morris, M.E., 2008. Balance during obstacle crossing following stroke. Gait Posture. 27, 23-30.

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. J Gerontol A Biol Sci Med Sci. 62, 537-542.

Stelmach, G.E., Worringham, C.J., 1985. Sensorimotor deficits related to postural stability. Implications for falling in the elderly. Clin Geriatr Med. 1, 679-694.

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. Hum Mov Sci. 27, 728-737.

Winter, D.A., 1995. Human balance and posture control during standing and walking. Gait Posture. 3, 193-214.

Wojcik, L.A., Thelen, D.G., Schultz, A.B., Ashton-Miller, J.A., Alexander, N.B., 1999. Age and gender differences in single-step recovery from a forward fall. J Gerontol A Biol Sci Med Sci. 54, M44-50.

Woollacott, M.H., Shumway-Cook, A., 2002. Attention and the control of posture and gait: A review of an emerging area of research. Gait Posture. 16, 1-14.

Figure 1.

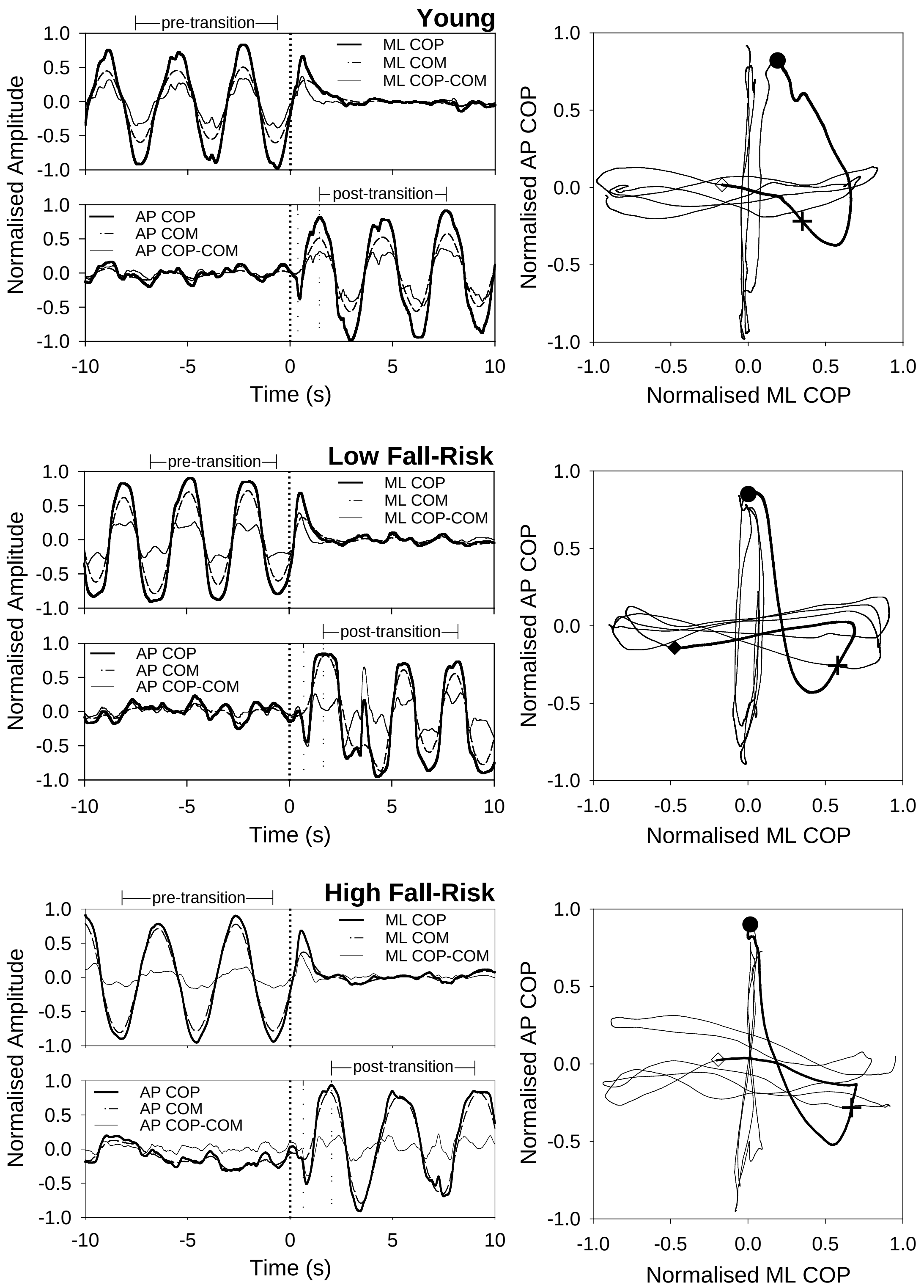
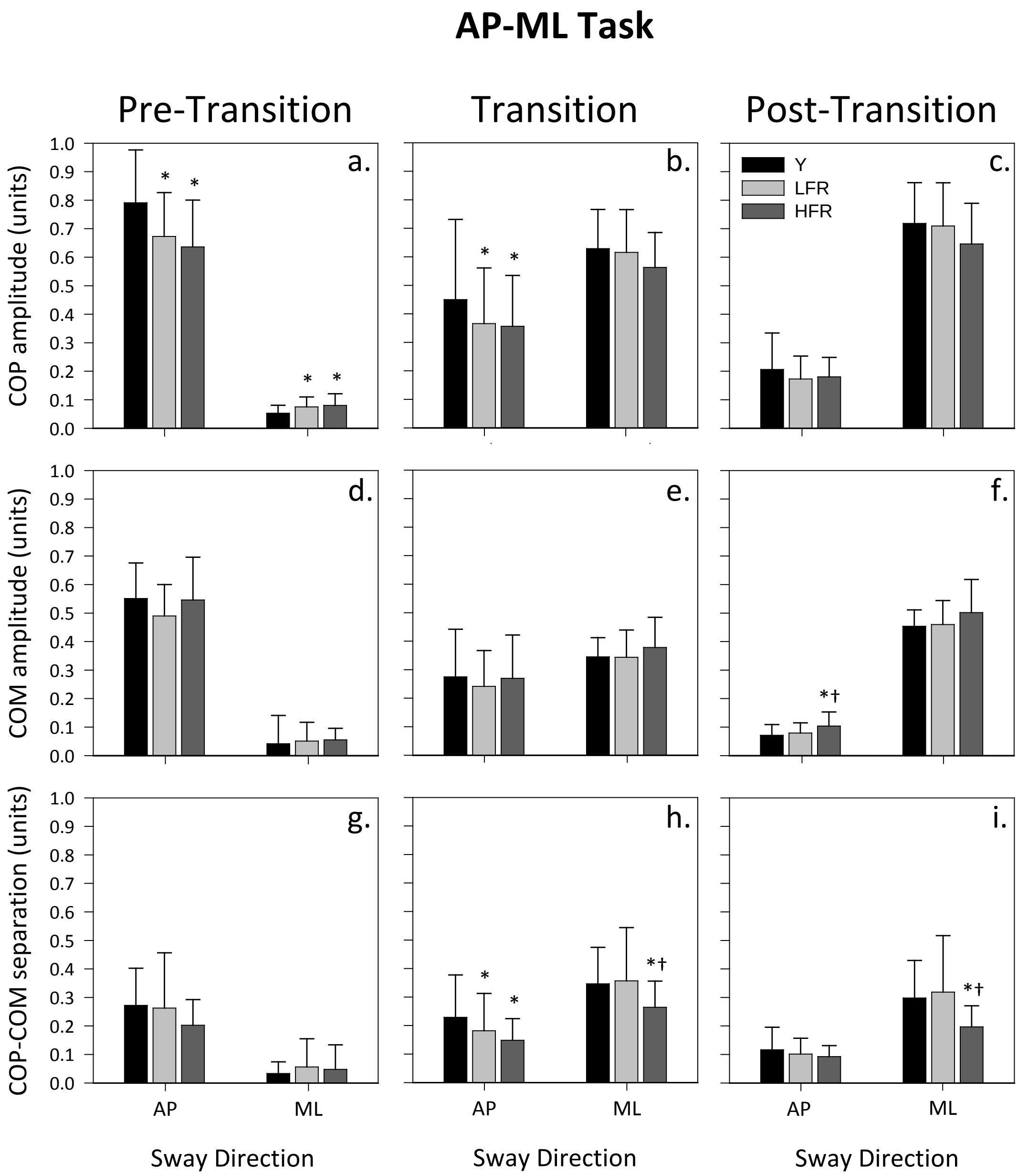
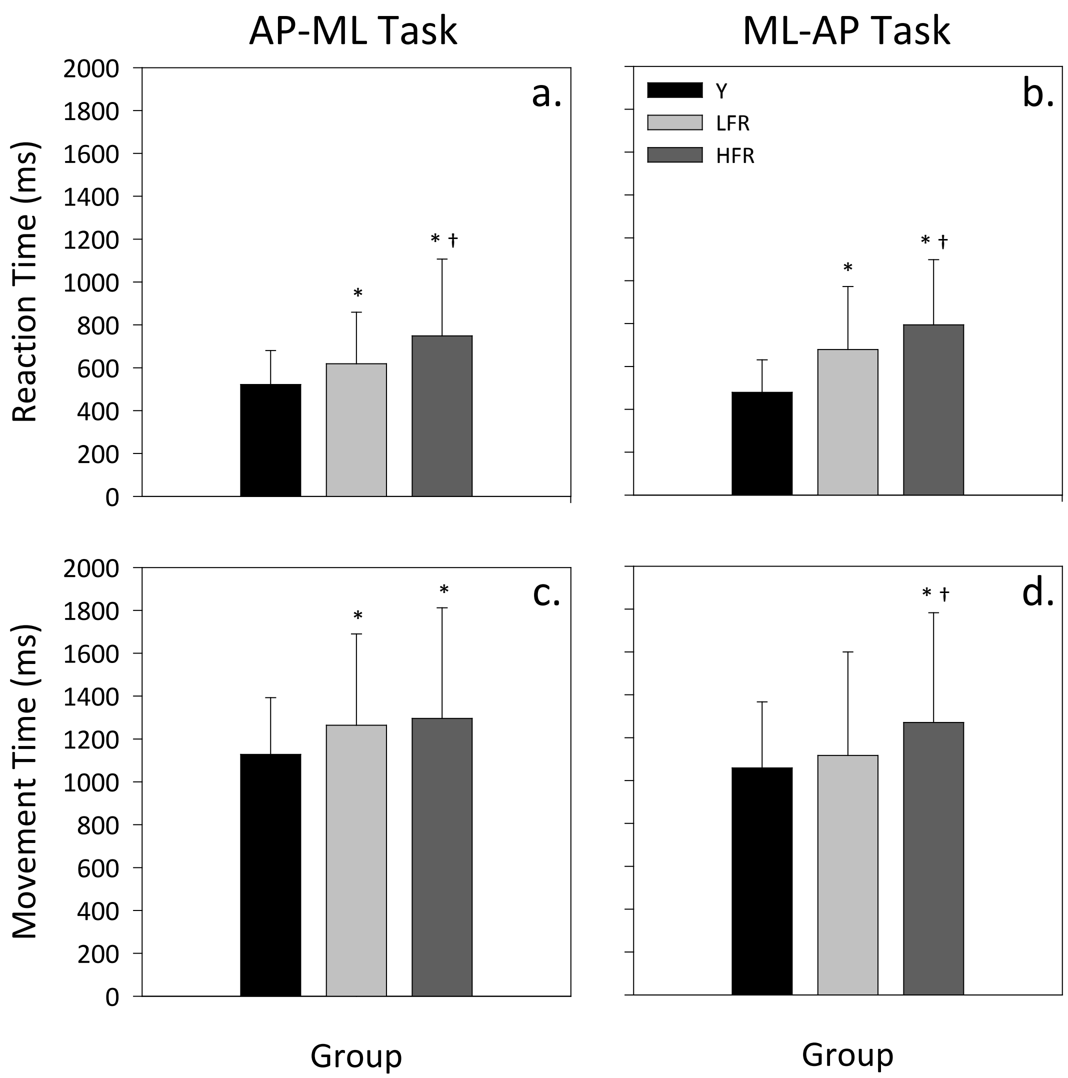

Young
pre-transition
post-transition
ML COP
ML COM
ML COP-COM
AP COP
AP COM
AP COP-COM
Normalised Amplitude
Time (s)
Normalised AP COP
Normalised ML COP
Low Fall-Risk
High Fall-Risk

Figure 2.



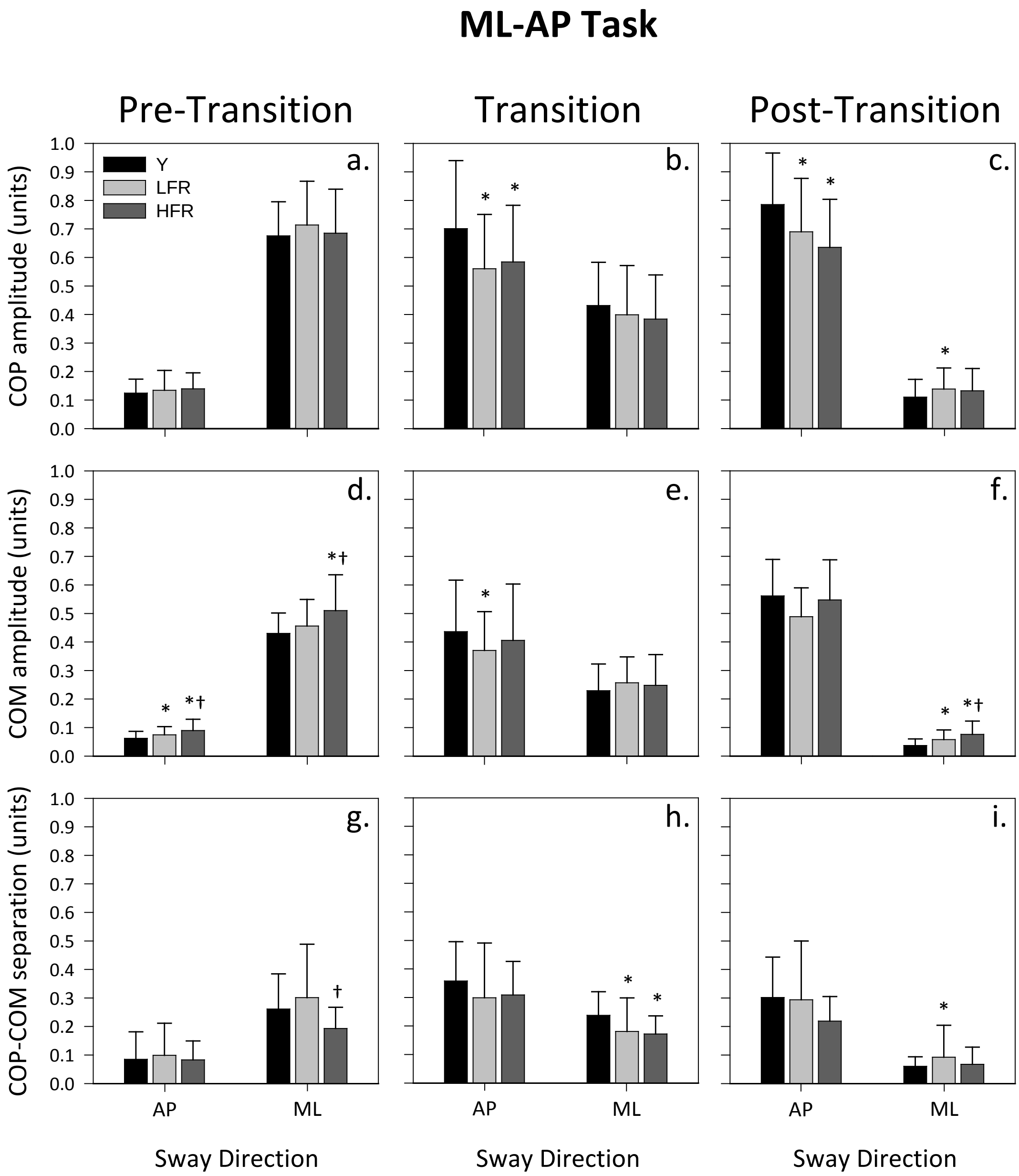
AP-ML Task
Pre-Transition
Transition
Post-Transition
COP amplitude (units)
COM amplitude (units)
COP-COM separation (units)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
a.
b.
c.
d.
e.
f.
g.
h.
i.
Y
LFR
HFR
*
*†
AP
ML
Sway Direction

Figure 3.



AP-ML Task
ML-AP Task
Reaction Time (ms)
Movement Time (ms)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
a.
b.
c.
d.
Y
LFR
HFR
* †
*
Group
Group

Figure 4.



ML-AP Task
Pre-Transition
Transition
Post-Transition
Y
LFR
HFR
a.
b.
c.
d.
e.
f.
g.
h.
i.
COP amplitude (units)
COM amplitude (units)
COP-COM separation (units)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
AP
ML
Sway Direction

Figure Captions.

Figure 1. Representative plots of normalised COP, COM and COP-COM amplitudes in the AP and ML directions during an ML-AP trial for young, low fall-risk, and high fall-risk participants in which a forward cue was presented. The time series plots illustrate ten seconds of data prior to, and following the onset of the cue (dot vertical line at t = 0 s). The reaction time period starts at the cue and ends at the vertical dash line (– –) and the movement time period starts at the dash line and ends at the vertical dash-dot line (— · —). Adjacent to the time plots are the corresponding normalised AP versus ML COP plots for each participant. The symbols represent the coordinate location of the COP when a specific event occurred. ◆ = cue onset; + = reaction time; ● = movement time. The bold path highlights the COP trajectory from cue onset to movement time. With respect to neutral stance (zero amplitude), positive and negative values denote that for the AP direction, the COP and COM are located forward and backward respectively, and that for the ML direction, the COP and COM are located right and left respectively.

Figure 2. Pre-transition, transition and post-transition amplitudes of the COP, COM, and COP-COM in the AP and ML directions for the young (Y), low fall-risk (LFR) and high fall-risk (HFR) groups for the AP-ML sway task. Values are means ± one standard deviation in normalised units. *Significantly different to young, $P < .05$. †High fall-risk significantly different to low fall-risk, $P < .05$.

Figure 3. Reaction and movement times of the young (Y), low fall-risk (LFR) and high fall-risk (HFR) groups during the AP-ML and ML-AP sway tasks. Values are means ± one standard

deviation. *Significantly different to young, $P < .05$. †High fall-risk significantly different to low fall-risk, $P < .05$.

Figure 4. Pre-transition, transition, and post-transition amplitudes of the COP, COM, and COP-COM in the AP and ML directions for the young (Y), low fall-risk (LFR) and high fall-risk (HFR) groups during the ML-AP sway task. Values are means ± one standard deviation in normalised units. *Significantly different to young, $P < .05$. †High fall-risk significantly different to low fall-risk, $P < .05$.

Tables.

**Table 1. Group Characteristics and Maximum Voluntary Sway COP Amplitudes**

| **Variable** | **Young** | **Low Fall-Risk** | **High Fall-Risk** | **F, *P* value** |
|---|---|---|---|---|
| ***Anthropometry*** | | | | |
| N (males, females) | 25 (13,12) | 32 (17,15) | 16 (10,6) | NA |
| Age (years) | 25 ± 4 | 74 ± 5 | 79 ± 7† | F = 719.19, *P* < .001 |
| Height (cm) | 173.2 ± 10.7 | 166.6 ± 10.5 | 166.4 ± 12.0 | F = 3.05, *P* = .054 |
| Mass (kg) | 70.8 ± 14.5 | 79.8 ± 14.0 | 75.7 ± 18.3 | F = 2.44, *P* = .094 |
| ***Fall Risk Assessment*** | | | | |
| PPA score | NA | 0.4 ± 0.5 | 1.8 ± 0.6† | F = 77.03, *P* < .001 |
| Fallen in previous year (%) | NA | 22 | 50 | NA |
| Modified Baecke score | NA | 16.3 ± 8.4 | 14.3 ± 9.3 | F = 0.50, *P* = .483 |
| FES-I | NA | 21.7 ± 6.3 | 26.3 ± 10.6 | F = 3.30, *P* = .076 |
| ***COP Amplitude*** | | | | |
| Forward (mm) | 146 ± 66 | 113 ± 48* | 103 ± 35* | F = 4.13, *P* = .020 |
| Backward (mm) | 87 ± 34 | 83 ± 38 | 61 ± 23 | F = 3.00, *P* = .057 |
| Left (mm) | 193 ± 86 | 156 ± 60* | 117 ± 39* | F = 6.36, *P* = .003 |
| Right (mm) | 202 ± 86 | 150 ± 62* | 119 ± 26* | F = 8.32, *P* < .001 |

Values are means ± one standard deviation. *Significantly different to Young, *P* < .05. †Significantly different to Low Fall-Risk, *P* < .05. PPA = Physiological Profile Assessment; FES-I = Falls Efficacy Scale International; COP = centre of pressure; NA = not available.