

What are the relations between voluntary postural sway measures and falls-history status in community-dwelling older adults?

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Running Head: Identifying fallers using voluntary sway

## **ABSTRACT**

**Objectives:** To determine whether a series of voluntary postural sway tasks could differentiate and accurately identify the falls-history status of older adults and to examine the relations between voluntary sway measures and falls-risk.

**Design:** Case control study.

**Setting:** University biomechanics laboratory.

**Participants:** Fifty-one healthy community-dwelling older adults aged 65-94 years that were divided into non-faller (N=35), single faller (N=10) and multiple faller (N=5) groups based on 12 months falls-history.

**Interventions:** Not applicable.

**Main Outcome Measures:** Participants underwent a falls-risk assessment using the Physiological Profile Assessment (PPA) and then performed six voluntary postural sway tasks. The tasks included maximum static leans, maximum voluntary sway, continuous voluntary sway, rapid initiation of voluntary sway, rapid termination of voluntary sway, and rapid orthogonal switches of voluntary sway between the anterior-posterior and medial-lateral directions. Centre of pressure amplitudes and reaction time measures were examined using analysis of covariance, Pearson's correlation, and discriminant function analyses.

**Results:** Multiple fallers had increased age, falls-risk, slower initiation, termination, and orthogonal switch reaction times, and reduced centre of pressure amplitude during sway initiation and continuous voluntary sway compared to non-fallers. Few differences were observed between the non-fallers and single fallers. Voluntary sway measures were significantly correlated with each other and with PPA score. Two postural reaction time measures and age identified 80% of multiple fallers

and 98% of non-multiple fallers. Similarly, PPA score and age identified 80% of multiple fallers and 100% of non-multiple fallers.

**Conclusions:** The slower and less effective balance responses of multiple fallers compared to non-fallers and the comparable sensitivity and specificity of PPA score and reactive voluntary sway measures indicates that postural reaction time is a strong determinant of falls-risk.

**Key words:** Postural balance; Ageing; Unintentional falls

### List of Abbreviations

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RT	reaction time
COP	centre of pressure
AP	anterior-posterior
ML	medial-lateral
PPA	Physiological Profile Assessment
ANCOVA	analysis of covariance

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## INTRODUCTION

The normal ageing process increases the susceptibility of older persons to falls. For community-living older adults aged 65 years and above, approximately 1 in 3 individuals fall at least once per year and 1 in 10 individuals fall on multiple occasions.<sup>1,2</sup> Given this high rate of falls, a major focus of falls-related research has been on the development of approaches to predict an individual's susceptibility to falls.<sup>3-5</sup> However, this is not a trivial undertaking because over 400 potential risk factors have been identified with falls.<sup>6</sup> For many older individuals, impaired balance emerges as the biggest falls risk factor.<sup>7</sup> Epidemiological studies have found that most falls result from an inability to rapidly recover from a loss of balance during daily activities.<sup>1,8</sup> Therefore, a key element in the ability to avoid a fall is the capacity to react quickly and effectively with the body<sup>9,10</sup> which is a task crucially dependent on sensory feedback, muscular strength, motor coordination, and reaction time (RT).<sup>11,12</sup> Simple quantitative assessments that emphasized speed of response during voluntary multidirectional body movements have accurately identified older individuals with increased falls-risk.<sup>9,13,14</sup>

Voluntary postural sway movements represent a simple approach to examining deficits in postural control which may contribute to falls. The 3 main categories of voluntary postural sway tasks include maximum voluntary leans held statically, continuous steady-state voluntary sway, and rapidly initiated voluntary sway movements performed under RT conditions. It has been found that maximum static lean amplitudes (c.f. Limits of Stability and Functional Reach tests), are weakly associated or non-predictive of falls in healthy older adults.<sup>15-19</sup> In contrast, reactive voluntary postural sway movements significantly differentiate between younger and older men,<sup>20</sup> and between young adults, and low and high falls-risk older adults.<sup>21</sup> For rapid orthogonal switches of voluntary postural sway between the anterior-posterior (AP) and medial-lateral (ML) directions, ageing and elevated falls-risk among the elderly results in slower RT, reduced centre of pressure (COP) response amplitudes, and altered postural coordination relations.<sup>20,21</sup> In the current study, it

was of interest to determine whether a series of voluntary postural sway tasks could differentiate between older adults with a recent history of no falls, a single fall, or multiple falls. The classification accuracies of the voluntary postural sway tasks for falls-history status were also contrasted with the classification accuracies of the Physiological Profile Assessment (PPA). The PPA is a valid and reliable predictor of falls among older adults as it differentiates between multiple fallers and non-multiple fallers with 75% accuracy.<sup>4</sup> As voluntary postural sway actions require significant contributions from the cognitive,<sup>22</sup> sensory,<sup>23</sup> and muscular systems,<sup>24</sup> RT and COP measures of sway performance may provide similar information on falls-risk compared to the PPA.

The general objective of this study was not to develop a new clinical test of falls-risk but rather to examine the factors related to the performance of voluntary postural sway which may contribute to falls-history status. The specific aims of this study were to examine the effect of falls-history status on the performance of voluntary postural sway tasks as assessed by RT and COP amplitude measures, and also to examine the strength of relationship between these measures and PPA score. It was hypothesized that (1) multiple fallers would have significantly slower RT and reduced COP amplitude compared to non-fallers, (2) voluntary sway measures would significantly identify the falls-history status of older adults with comparable accuracy to PPA score, and (3) the tasks with the best capacity for discriminating falls-history status would involve a reaction response rather than a static lean movement.

## **METHODS**

### **Participants**

Fifty-one older adults aged 65 to 94 years were recruited from retirement villages and independent housing within the local community. Participants 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 guidelines of the Institutional Human Research Ethics Committee were followed during all experimental procedures.

### **Experimental Design and Protocol**

Participants attended the laboratory on two occasions. All data were collected by the primary author (M.G. Tucker). On the first visit, participants completed a questionnaire regarding their medical history and falls-history. A fall was defined as an event within the previous 12 months during activities of daily living which resulted in a person coming to rest unintentionally on the ground or other lower level, and not as the result of a major intrinsic event or an overwhelming hazard. Individuals reporting no falls were classified as non-fallers, individuals reporting 1 fall were classified as single fallers, and individuals reporting 2 or more falls were classified as multiple fallers. After measurement of participant characteristics (e.g. age, gender, height, mass), a falls-risk assessment was performed using the short-form PPA.<sup>3</sup> Briefly, this assessment included tests of visual contrast sensitivity, knee joint proprioception, leg extension strength of the dominant limb, visual RT using a hand-press response, and amplitude of postural sway whilst standing for 30 s on a rubber foam mat.<sup>4</sup> Scores from each test were combined to yield a falls-risk score that ranged from -2 (very low falls-risk) to 4 (very marked falls-risk).<sup>4</sup>

On the second visit, participants underwent voluntary postural sway testing. The voluntary postural sway assessments have been described previously.<sup>20,21</sup> Initially, participants were fitted with a light-weight, non-restrictive safety harness which was secured to the roof of the laboratory using a safety line. Participants then stood on a Kistler Type 9287A force plate<sup>b</sup> which was used to collect the COP in the AP and ML directions at 1000 Hz. The following 6 postural reaction and voluntary sway tasks were assessed:

1. Maximum static leans: Without losing balance, participants leaned as far as they could in the forward, backward, left and right directions and held their maximum lean position for 4 s (fig 1a).
2. Maximum voluntary sway: Participants swayed maximally for three continuous cycles in the AP direction and then the ML direction (fig 1b).
3. Initiation of voluntary sway: Participants initiated AP or ML voluntary sway as rapidly as possible in response to an auditory cue following a random 5-10 s period of quiet stance (fig 1c).
4. Orthogonal switches of voluntary sway: Following 2-5 oscillations of voluntary sway, participants switched their sway to the orthogonal direction as rapidly as possible in response to an auditory cue (e.g. sway in the AP direction before rapidly switching sway to the ML direction, fig 1d).
5. Termination of voluntary sway: Participants terminated AP or ML voluntary sway as rapidly as possible in response to a 'stop' auditory cue following 2-5 oscillations of voluntary sway (fig 1e).
6. Continuous voluntary sway: Participants performed 4-5 oscillations of AP or ML voluntary sway at their preferred frequency between the initiation and termination tasks (fig 1f).

<fig 1>

Participants were instructed to restrict motion to the ankle joint during AP sway movements, and to sequentially load and unload each leg during ML sway movements.<sup>20,21</sup> For the initiation and orthogonal switch tasks, participants were presented with a 'forward' or 'backward', or a 'left' or 'right' auditory cue. Following a forward or backward reaction, participants immediately commenced and continued AP voluntary postural sway. Following a left or right reaction, participants immediately commenced and continued ML voluntary postural sway. Two trials were collected for maximum voluntary sway and maximum static lean tasks, and 20 trials (10 AP and 10 ML) were collected for the initiation, orthogonal switch and termination tasks. Trials in which participants lost their balance and stepped or responded in the incorrect direction were repeated.

### **Voluntary Sway Measures**

RTs and COP response amplitudes were measured for the initiation, orthogonal switch, and termination tasks. Start RT (initiation task) and switch RT (orthogonal switch task) were the periods from the auditory cue until the COP exceeded a threshold of 2 SDs of baseline data which was calculated 3 s prior to the cue.<sup>21</sup> Stop RT (termination task) was the period from the stop cue until the direction of COP oscillation reversed. Response amplitudes for sway initiation and orthogonal switches of sway were measured as the peak of AP or ML COP displacement in the direction of the auditory cue. Termination response amplitude was the peak of AP or ML COP amplitude at the end of the stop RT period.

Ranges of COP displacement in the AP and ML directions were measured for the maximum static lean, maximum voluntary sway, and continuous voluntary sway tasks. For each task, a peak-detection algorithm identified the peak forward, backward, left and right COP amplitudes. The peak amplitudes were averaged for each direction, and then the average peak amplitudes were used to calculate the AP and ML COP ranges. The AP and ML ranges were normalized to the participant's

height and mass for the maximum static lean and maximum voluntary sway tasks. All data analysis was performed using Matlab software<sup>c</sup> version 7.6.0 (Release 2008a).

### **Statistical Analysis**

Analysis of Covariance (ANCOVA) was used to test for main group effects of falls-history status (3 levels: non-fallers, single fallers, multiple fallers) in participant characteristics and voluntary sway measures. Planned contrasts were used to identify specific between-groups differences. Age was used as the covariate for all statistical tests. The relations between the voluntary sway measures identified as significantly different between groups and the relations between these voluntary sway measures and PPA score were examined using Pearson product-moment partial correlation coefficients adjusted for age. Compound measures for this analysis represented the average of that measure over the AP and ML directions.

Forwards stepwise discriminant analyses were performed with sensitivities, specificities, positive and negative likelihood ratios and classification coefficients provided for (1) age, (2) PPA score, (3) age and PPA score, (4) the first selected voluntary sway measure, and (5) all selected voluntary sway and age measures. Participants were divided into non-multiple fallers and multiple fallers for discriminant analysis because no significant differences were identified between the non-fallers and single fallers in the ANCOVA analysis. The significance of each analysis was tested using the Wilks' Lambda statistic where values closer to 0 and 1 denote high and low between-groups discrimination respectively.<sup>25</sup> Statistical analyses were performed using SAS<sup>d</sup> version 9.1 with significance accepted at  $P < .05$ .

## RESULTS

### Participant Characteristics of the Falls Groups

Out of the 51 older adults that participated in the study, 36 individuals (70.6%) reported no falls, 10 individuals (19.6%) reported falling once, and 5 individuals (9.8%) reported falling on 2 or more occasions. The multiple fallers were significantly older and had a higher PPA score compared to the non-fallers and single fallers ( $P's < .05$ ) (table 1). All participants were able to complete the required number of trials following episodes of balance loss or incorrect responses.

<table 1>

### Effect of Falls-History Status on Voluntary Sway Measures

Multiple fallers had significantly slower switch RT during AP-ML and ML-AP orthogonal switches of voluntary sway, slower stop RT during termination of ML voluntary sway, and reduced COP amplitude during initiation of AP and ML voluntary sway and continuous voluntary AP and ML sway compared to non-fallers ( $P's < .05$ ) (table 2). Multiple fallers also had slower start RT during initiation of AP voluntary sway and a higher percentage of incorrect responses and balance loss trials and compared to the single fallers and non-fallers ( $P's < .05$ ).

<table 2>

### Relations between Voluntary Sway Measures

Scatter plots for the relations between variables identified as significantly different between groups are displayed in fig 2. Correlations between the AP and ML directions for measures of switch RT, sway initiation amplitude and continuous voluntary sway amplitude ranged from 0.72 to 0.85 (fig 2a-c). Start RT to initiate AP sway was significantly correlated with sway initiation AP COP amplitude ( $r = -0.51$ ) (fig 2d), and also with the stop RT to terminate ML sway ( $r = 0.44$ ) (fig 2e). Compound

orthogonal switch RT was significantly correlated with the compound measures of sway initiation amplitude ( $r=-0.38$ ) (fig 2f), and continuous voluntary sway range ( $r=-0.44$ ) (fig 2g). Compound continuous voluntary sway range was also significantly correlated with compound sway initiation amplitude ( $r=0.93$ ) (fig 2h).

<fig 2>

### **Relations between Voluntary Sway Measures and PPA Score**

Scatter plots for the relations between PPA score and voluntary sway measures are displayed in fig 3. Correlations of PPA score with age, and the initiation, orthogonal switch and termination RTs were significant and ranged from 0.33 to 0.45 (fig 3a-e). PPA score was also significantly correlated with sway initiation and continuous voluntary sway COP amplitudes for both AP and ML directions with  $r$  values between -0.42 and -0.50 (fig 3f-i).

<fig 3>

### **Classification of Non-Multiple Fallers and Multiple Fallers using Age, PPA Score and Voluntary Sway Measures**

The results of the discriminant analyses are presented in table 3. Age alone, PPA score alone, and age combined with PPA score significantly discriminated between the multiple fallers and non-multiple fallers ( $P's<.001$ ). The first voluntary sway measure selected as the strongest discriminator between groups was stop RT to terminate ML sway ( $P<.001$ ). With all of the significantly different voluntary sway measures available for selection, the selected measures were stop RT to terminate ML sway, age, and start RT to initiate AP sway ( $P<.001$ ).

<table 3>

## DISCUSSION

The results confirmed our hypothesis that multiple fallers would have slower RT during voluntary postural sway tasks compared to non-fallers. Not only was stop RT to terminate ML sway identified as the strongest overall discriminator of falls-history status from the voluntary sway measures, the multiple fallers also had RTs which were 20-60% slower compared to the non-fallers for the initiation, termination, and orthogonal switch tasks. These slowed postural reactions would seem detrimental to the ability to avoid falls because there is often a limited amount of time in which to initiate an effective response to a perturbation of balance.<sup>10-12,26</sup> In agreement with our findings, the best determinants of falls-history status from the PPA subtests were hand-press RT, and the ability to regulate postural sway oscillations whilst standing on a challenging foam surface. Therefore, the findings of the study strongly suggest that slower voluntary postural reactions are an important determinant of falls among older people.<sup>9,14,18</sup>

Multiple fallers had reduced COP amplitudes compared to non-fallers when rapidly initiating sway and when performing continuous voluntary sway in the AP and ML directions. These results indicate that the multiple fallers had weaker postural responses to shift the COP which is a reflection of their reduced standing stability. As the multiple fallers also lost their balance more frequently during the 6 sway tasks, our findings suggest they had difficulty in rapidly correcting whole body momentum.<sup>21,27</sup> The increased PPA scores of the multiple fallers compared to the non-fallers and single fallers indicates that they had increased falls-risk and poor balance control because of impairments to their postural control physiology.<sup>4</sup> The significant correlations between PPA score and the RT and COP measures suggests that a combination of cognitive, sensory, strength, and coordination factors influenced the group differences in voluntary postural sway performance.

The second hypothesis was also confirmed as the voluntary sway measures significantly identified falls-history status with comparable accuracy to PPA score. Age alone was sufficient to classify a high percentage of multiple faller and non-multiple faller individuals, which confirms that advanced age is a risk factor for multiple falls.<sup>1</sup> Two RT measures (stop RT ML and start RT AP) and age improved sensitivity and specificity, and the likelihood ratios for this discriminant model further demonstrated that these measures formed a useful classification model for multiple falls status. Not only were sensitivity and specificity similar between voluntary sway measures and PPA score, it was also found that voluntary sway measures were significantly correlated with PPA score. Therefore, voluntary sway measures provide important information regarding falls-risk and may have some clinical value.<sup>21,28</sup> The significant relations among the voluntary sway measures also indicates that they provided some overlapping information across tasks and response directions. RT and COP measures other than those identified as the best discriminators between groups may thus provide useful information regarding voluntary postural sway performance.

The study findings also confirmed our prediction that reactive postural tasks would be better predictors of falls-history status compared to static leaning actions. Significant differences were detected between multiple fallers and non-fallers for sway tasks involving a reaction response. In contrast, no significant differences were observed for the maximum lean or voluntary sway tasks, a finding which is consistent with previous reports.<sup>15-19,21</sup> The maintenance of a static postural position may be less challenging to the sensorimotor and muscular systems compared to a dynamic reaction movement.<sup>29</sup> Alternatively, older adults regardless of their falls-risk may adopt a cautious approach to balance maintenance when approaching the limits of stability.<sup>30,31</sup> Furthermore, the majority of differences in sway measures were observed between the multiple fallers and non-fallers. This indicates that voluntary postural sway measures have the best capacity to identify older adults with

balance impairments that are systematically related to falls rather than to identify older adults with more subtle balance limitations who may fall only once within 12 months.<sup>32,33</sup>

The findings of this study must be interpreted with caution as the retrospective questionnaires may have underestimated the number of falls recalled by participants.<sup>2,34</sup> A retrospective study also cannot determine whether the differences observed between groups contributed to the falls or were simply a consequence of the falls. What our study established however is that the variables we investigated were significantly different between groups, and more importantly, that they were able to discriminate retrospective falls with a high degree of sensitivity and specificity. The PPA may also be more suitable as a prospective rather than retrospective measure of falls-risk.<sup>4</sup> Although the sample size for this study was relatively small (N=51), the group size proportions of the fallers (29%) and multiple fallers (10%) are consistent with the accepted rates of falls among community-dwelling older people.<sup>1,2</sup>

In conclusion, the ability to react quickly with the whole body and to regulate voluntary sway under dynamic and challenging conditions is a strong indicator of a recent history of multiple falls in healthy community-dwelling older people. The slower postural reactions and less effective COP stabilizing responses of the multiple fallers compared to non-fallers, and also the comparable classification accuracies between PPA score and reactive voluntary sway measures suggests that reactive postural sway tasks provide important information regarding falls-risk.

## REFERENCES

1. Lord SR, Ward JA, Williams P, Anstey KJ. An epidemiological study of falls in older community-dwelling women: the Randwick falls and fractures study. *Aust J Public Health* 1993;17:240-5.
2. Hill K, Vrantsidis F, Haralambous B, Fearn M, Smith R, Murray K, Sims J, Dorevitch M. An analysis of research on preventing falls and falls injury in older people: community, residential care and hospital settings. Canberra: National Ageing Research Institute; 2004.
3. Perell KL, Nelson A, Goldman RL, Luther SL, Prieto-Lewis N, Rubenstein LZ. Fall risk assessment measures: an analytic review. *J Gerontol A Biol Sci Med Sci* 2001;56A:M761-6.
4. Lord SR, Menz HB, Tiedemann A. A physiological profile approach to falls risk assessment and prevention. *Phys Ther* 2003;83:237-52.
5. Scott V, Votova K, Scanlan A, Close J. Multifactorial and functional mobility assessment tools for fall risk among older adults in community, home-support, long-term and acute care settings. *Age Ageing* 2007;36:130-9.
6. Oliver D, Britton M, Seed P, Martin FC, Hopper AH. Development and evaluation of evidence based risk assessment tool (STRATIFY) to predict which elderly inpatients will fall: case-control and cohort studies. *BMJ* 1997;315:1049-53.
7. Close JC. Prevention of falls in older people. *Disabil Rehabil* 2005;27:1061-71.
8. Bradley C, Pointer S. Hospitalisations due to falls by older people, Australia 2005-06. Injury research statistics series number 50. INJCAT 122. Adelaide: Australian Institute of Health and Welfare; 2009.
9. Lord SR, Fitzpatrick RC. Choice stepping reaction time: a composite measure of falls risk in older people. *J Gerontol A Biol Sci Med Sci* 2001;56:M627-32.
10. Maki BE, McIlroy WE. Control of rapid limb movements for balance recovery: age-related changes and implications for fall prevention. *Age Ageing* 2006;35(Suppl 2):ii12-8.

11. Grabiner MD, Enoka RM. Changes in movement capabilities with aging. *Exerc Sport Sci Rev* 1995;23:65-104.
12. Stelmach GE, Worringham CJ. Sensorimotor deficits related to postural stability. Implications for falling in the elderly. *Clin Geriatr Med* 1985;1:679-94.
13. Dite W, Temple VA. A clinical test of stepping and change of direction to identify multiple falling older adults. *Arch Phys Med Rehabil* 2002;83:1566-71.
14. Melzer I, Kurz I, Shahar D, Levi M, Oddsson L. Application of the voluntary step execution test to identify elderly fallers. *Age Ageing* 2007;36:532-7.
15. Thomas JI, Lane JV. A pilot study to explore the predictive validity of 4 measures of falls risk in frail elderly patients. *Arch Phys Med Rehabil* 2005;86:1636-40.
16. Boulgarides LK, McGinty SM, Willett JA, Barnes CW. Use of clinical and impairment-based tests to predict falls by community-dwelling older adults. *Phys Ther* 2003;83:328-39.
17. Melzer I, Benjuya N, Kaplanski J. Postural stability in the elderly: a comparison between fallers and non-fallers. *Age Ageing* 2004;33:602-7.
18. Brauer SG, Burns YR, Galley P. A prospective study of laboratory and clinical measures of postural stability to predict community-dwelling fallers. *J Gerontol A Biol Sci Med Sci* 2000;55:M469-76.
19. Wallmann HW. Comparison of elderly nonfallers and fallers on performance measures of functional reach, sensory organization, and limits of stability. *J Gerontol A Biol Sci Med Sci* 2001;56:M580-3.
20. Tucker MG, Kavanagh JJ, Barrett RS, Morrison S. Age-related differences in postural reaction time and coordination during voluntary sway movements. *Hum Mov Sci* 2008;27:728-37.
21. Tucker MG, Kavanagh JJ, Morrison S, Barrett RS. Voluntary sway and rapid orthogonal transitions of voluntary sway in young adults, and low and high fall-risk older adults. *Clin Biomech (Bristol, Avon)* 2009;24:597-605.

22. Lajoie Y, Teasdale N, Bard C, Fleury M. Attentional demands for static and dynamic equilibrium. *Exp Brain Res* 1993;97:139-44.
23. Kavounoudias A, Roll R, Roll JP. The plantar sole is a 'dynamometric map' for human balance control. *Neuroreport* 1998;9:3247-52.
24. Melzer I, Benjuya N, Kaplanski J, Alexander N. Association between ankle muscle strength and limit of stability in older adults. *Age Ageing* 2009;38:119-23.
25. Klecka WR. *Discriminant Analysis*. Beverly Hills: Sage Publications; 1980.
26. Pavol MJ, Owings TM, Foley KT, Grabiner MD. Mechanisms leading to a fall from an induced trip in healthy older adults. *J Gerontol A Biol Sci Med Sci* 2001;56:M428-37.
27. Cao C, Schultz AB, Ashton-Miller JA, Alexander NB. Sudden turns and stops while walking: kinematic sources of age and gender differences. *Gait Posture* 1998;7:45-52.
28. Rose DJ, Clark S. Can the control of bodily orientation be significantly improved in a group of older adults with a history of falls? *J Am Geriatr Soc* 2000;48:275-82.
29. Prioli AC, Cardozo AS, de Freitas Junior PB, Barela JA. Task demand effects on postural control in older adults. *Hum Mov Sci* 2006;25:435-46.
30. Hahn ME, Chou LS. Age-related reduction in sagittal plane center of mass motion during obstacle crossing. *J Biomech* 2004;37:837-44.
31. Menz HB, Lord SR, Fitzpatrick RC. Age-related differences in walking stability. *Age Ageing* 2003;32:137-42.
32. Ivers RQ, Cumming RG, Mitchell P, Attebo K. Visual impairment and falls in older adults: the Blue Mountains Eye Study. *J Am Geriatr Soc* 1998;46:58-64.
33. Nevitt MC, Cummings SR, Hudes ES. Risk factors for injurious falls: a prospective study. *J Gerontol* 1991;46:M164-70.
34. Ganz DA, Higashi T, Rubenstein LZ. Monitoring falls in cohort studies of community-dwelling older people: effect of the recall interval. *J Am Geriatr Soc* 2005;53:2190-4.

## **Suppliers**

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Barker St, Randwick, NSW 2031, Australia.
- b. Kistler Instrument Corporation, 75 John Glenn Drive, Amherst, NY 14228, United  
States.
- c. The Mathworks Inc, 3 Apple Hill Dr, Natick, MA 01760, United States.
- d. SAS Institute Inc, 100 SAS Campus Dr, Cary, NC 27513, United States.

## TABLES

**Table 1: Participant Characteristics of the Falls Groups.**

<i>Descriptive Measures</i>	<i>Non-Fallers (n = 36)</i>	<i>Single Fallers (n = 10)</i>	<i>Multiple Fallers (n = 5)</i>	<i>Group Effect P Value</i>
Age (yr)	74 (5)	75 (5)	86 (7)*†	< .001
Gender (% men)	56	50	40	NA
Height (cm)	168 (11)	164 (9)	157 (13)	.068
Mass (kg)	81 (20)	79 (15)	62 (16)	.108
PPA score	0.61 (0.69)	0.82 (0.60)	2.31 (0.76)*†	< .001
<i>PPA Subtests</i>				
Visual contrast sensitivity (dB)	20 (1.4)	20 (0.9)	18 (2.2)	.201
Knee proprioception (°)	2.0 (1.2)	1.9 (1.0)	2.8 (1.0)	.376
Leg extension strength (kg)	40.6 (17.4)	34.5 (9.0)	20.3 (3.4)	.069
Hand RT (ms)	227 (30)	233 (38)	305 (46) *†	< .001
Sway on foam (mm)	154 (55)	182 (79)	255 (59)*	.017

NOTES. Values are mean with standard deviation in parentheses. \*Significantly different to non-

fallers,  $P < .05$ . †Multiple fallers significantly different to single fallers,  $P < .05$ . NA = not available.

**Table 2: Differences between Non-Fallers, Single Fallers and Multiple Fallers in RT and COP**

**Amplitude Measures for the Voluntary Sway Tasks.**

Voluntary Sway Task	Non-Fallers	Single Fallers	Multiple Fallers	Group Effect P Value
<i>General Performance</i>				
Incorrect responses (% trials)	2.7 (3.2)	2.1 (2.9)	9.6 (12.6)*†	.032
Loss of balance (% trials)	0.5 (1.5)	0.2 (0.7)	5.1 (7.2)*†	.006
<i>Maximum Static Leans</i>				
AP COP range (units)	0.94 (0.35)	0.90 (0.33)	1.04 (0.64)	.841
ML COP range (units)	1.69 (0.62)	1.56 (0.54)	1.73 (0.92)	.839
<i>Maximum Voluntary Sway</i>				
AP COP range (units)	1.02 (0.39)	0.96 (0.44)	1.37 (0.46)	.251
ML COP range (units)	1.81 (0.72)	1.60 (0.71)	1.88 (0.40)	.675
<i>Continuous Voluntary Sway</i>				
AP COP range (mm)	154 (31)	136 (36)	109 (24)*	.033
ML COP range (mm)	261 (49)	234 (47)	183 (51)*	.019
<i>Initiation of Voluntary Sway</i>				
Start AP reaction time (ms)	492 (146)	543 (195)	792 (197)*†	.009
Start ML reaction time (ms)	434 (120)	397 (81)	548 (117)	.116
AP COP response (mm)	73 (14)	65 (16)	51 (6)*	.016
ML COP response (mm)	120 (21)	107 (24)	91 (14)*	.029
<i>Switches of Voluntary Sway</i>				
Switch ML-AP reaction time (ms)	664 (140)	743 (141)	888 (118)*	.015
Switch AP-ML reaction time (ms)	613 (114)	695 (113)	838 (205)*	.005
ML-AP COP response (mm)	75 (16)	70 (15)	52 (9)	.052
AP-ML COP response (mm)	119 (24)	111 (23)	88 (17)	.082
<i>Termination of Voluntary Sway</i>				
Stop AP reaction time (ms)	490 (70)	548(81)	536 (118)	.084
Stop ML reaction time (ms)	549 (64)	588 (80)	660 (105)*	.011
AP COP response (mm)	56 (15)	50 (18)	44 (7)	.291
ML COP response (mm)	98 (23)	88 (21)	71 (29)	.090

NOTES. Values are mean with standard deviation in parentheses. \*Significantly different to non-

fallers,  $P < .05$ . †Multiple fallers significantly different to single fallers,  $P < .05$ . For the orthogonal

switches of voluntary sway task, ML-AP represents a switch of ML to AP voluntary sway, and AP-ML

represents a switch of AP to ML voluntary sway.

**Table 3: Discriminant Variables, Classification Accuracies, Likelihood Ratios, and Classification Equations for the Non-Multiple Fallers (NMF; prior probability = 90%) and Multiple Fallers (MF; prior probability = 10%).**

Discriminant Variables	Sensitivity (MF)	Specificity (NMF)	Likelihood Ratio (+)	Likelihood Ratio (-)	Wilks' Lambda	Classification Equations
Age	60*	98*	27.60	0.41	0.70	$MF = (3.19 \times age) - 138.96$ $NMF = (2.77 \times age) - 103.36$
PPA score	60*	100*	0†	0.40	0.65	$MF = (4.98 \times PPA_{score}) - 8.07$ $NMF = (1.42 \times PPA_{score}) - 0.57$
PPA score + age	80*	100*	0†	0.2	0.51	$MF = (4.78 \times PPA_{score}) + (3.18 \times age) - 144.26$ $NMF = (1.25 \times PPA_{score}) + (2.77 \times age) - 103.72$
StopRT <sub>ML</sub>	60*	96	13.80	0.42	0.69	$MF = (0.134 \times StopRT_{ML}) - 50.16$ $NMF = (0.103 \times StopRT_{ML}) - 28.60$
StopRT <sub>ML</sub> + age + StartRT <sub>AP</sub>	80*	98*	36.80	0.20	0.55	$MF = (0.038 \times StopRT_{ML}) + (2.93 \times age) + (0.018 \times StartRT_{AP}) - 148.84$ $NMF = (0.023 \times StopRT_{ML}) + (2.62 \times age) + (0.009 \times StartRT_{AP}) - 106.33$

\*Significantly higher compared to prior probability using one-tailed z-test,  $P < .05$ . †Low score but high positive likelihood ratio paradox. StartRT<sub>AP</sub> is the reaction time to initiate AP sway and StopRT<sub>ML</sub> is the reaction time to terminate ML sway. To classify cases, age (years), PPA score (unitless), and reaction time (ms) were entered into the appropriate MF and NMF equations. Each case was assigned to the group for which it had the highest classification score.

# FIGURES

Fig 1.

## Representative Data

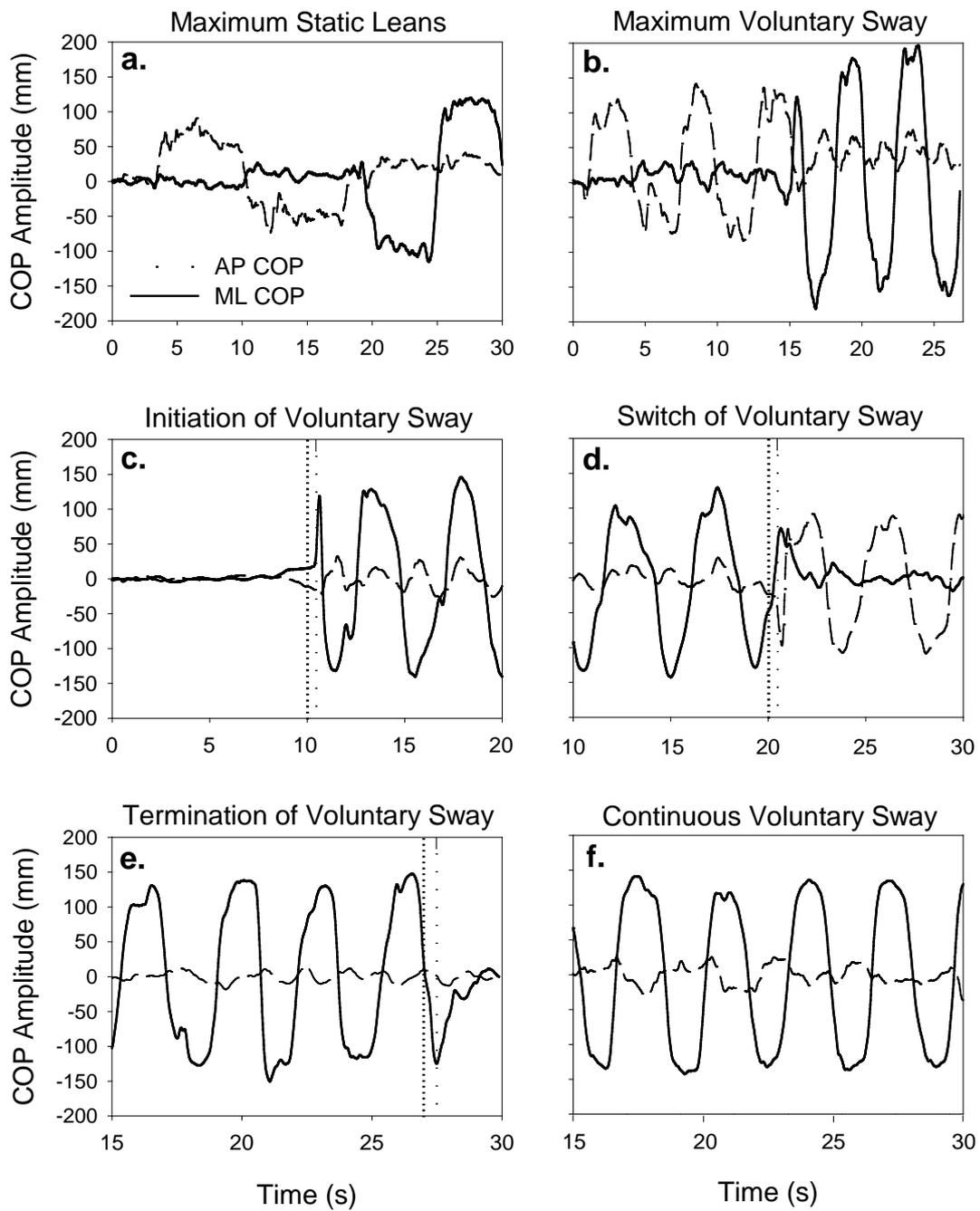


Fig 2.

### Scatter Plots of Voluntary Sway Measures

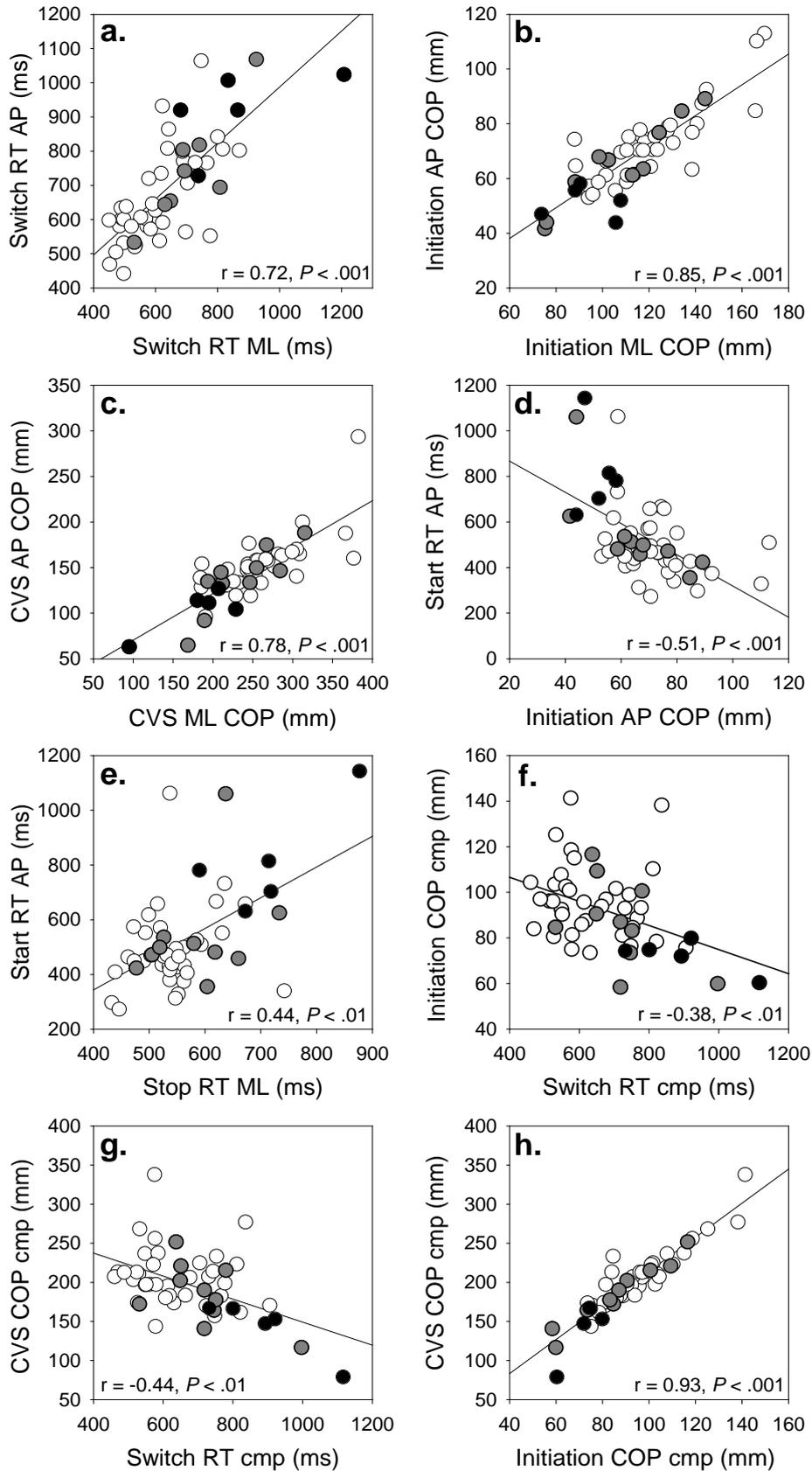
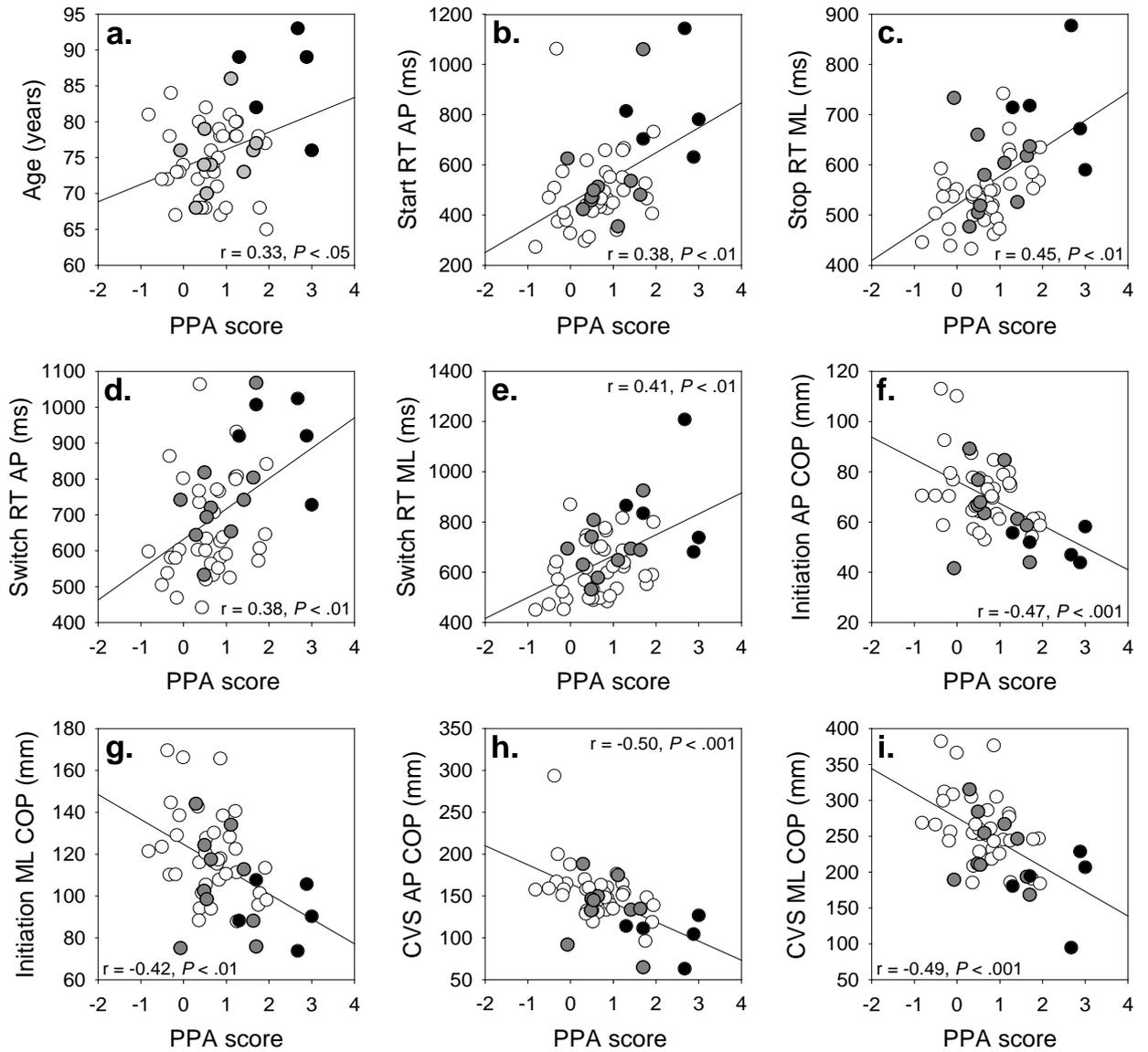


Fig 3.

### Scatter Plots of Voluntary Sway Measures and PPA Score



## FIGURE CAPTIONS

**Fig 1.** Sample COP data from the six voluntary postural sway tasks assessed in this study: (a) maximum static leans, (b) maximum voluntary sway, (c) initiation of voluntary sway, (d) orthogonal switches of voluntary sway, (e) termination of voluntary sway, and (f) continuous voluntary sway. For the initiation, termination, and orthogonal switch tasks, the dotted vertical line represents the onset of the auditory cue, and the dashed vertical line represents the participant's RT to the stimulus.

**Fig 2.** Scatter plots of non-faller (○ white circles), single faller (● gray circles), and multiple faller (● black circles) participant data with fitted linear regression lines for (a) switch RT AP and switch RT ML, (b) sway initiation AP and ML amplitude, (c) continuous voluntary sway AP and ML amplitude, (d) start RT AP and sway initiation AP amplitude, (e) start RT AP and stop RT ML, (f) sway initiation compound amplitude and switch RT compound, (g) continuous voluntary sway compound amplitude and switch RT compound, and (h) continuous voluntary sway compound amplitude and sway initiation compound amplitude. A compound measure is the average of that measure over the AP and ML directions. CVS = continuous voluntary sway; Cmp = compound. The  $r$  values represent the age-adjusted partial correlation coefficient.

**Fig 3.** Scatter plots of non-faller (○ white circles), single faller (● gray circles), and multiple faller (● black circles) participant data with fitted linear regression lines for PPA score and (a) age, (b) start RT AP, (c) stop RT ML, (d) switch RT AP, (e) switch RT ML, (f) sway initiation AP amplitude, (g) sway initiation ML amplitude, (h) continuous voluntary sway AP amplitude, and (i) continuous voluntary sway ML amplitude. CVS = continuous voluntary sway. The  $r$  values for plots 3b-3i represent the age-adjusted partial correlation coefficient.