34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

Displacement of centre of mass during quiet standing assessed using accelerometry in older fallers and non-fallers

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Abstract — **Postural sway during quiet standing is associated with falls risk in older adults. The aim of this study was to investigate the utility of a range of accelerometer-derived parameters of centre of mass (COM) displacement in identifying older adults at risk of falling. A series of instrumented standing balance trials were performed to investigate postural control in a group of older adults, categorised as fallers or non-fallers. During each trial, participants were asked to stand as still as possible under two conditions: comfortable stance (six repetitions) and semi-tandem stance (three repetitions). A tri-axial accelerometer was secured to the lower back during the trials. Accelerometer data were twice integrated to estimate COM displacement during the trials, with numerical techniques used to reduce integration error. Anterior-posterior (AP) and medial-lateral (ML) sway range, sway length and sway velocity were examined, along with root mean squared (RMS) acceleration. All derived parameters significantly discriminated fallers from non-fallers during both comfortable and semi-tandem stance. Results indicate that these accelerometer-based estimates of COM displacement may improve the discriminative power of quiet standing falls risk assessments, with potential for use in unsupervised balance assessment.**

I. Introduction

Balance during quiet standing is known to deteriorate with age [1], and is also associated with falls risk [2, 3]. Balance impairments affect quality of life, due to inability to perform activities of daily living caused by physical decline or increased fear of falling. Incidence of falling increases with age, with one in three adults aged over 65 falling every year [4]. Injuries sustained due to falls in the elderly result in significant economic and social burden. Additionally, falls have been identified as the most common cause of injury-related death for people over 65 years of age [5]. For these reasons, there is a continued need to increase knowledge of risk factors for falling, and to develop new methods to assess balance and falls risk.

Manuscript received June 03, 2012. This research was completed as part of a wider programme of research within the TRIL Centre, (Technology Research for Independent Living). The TRIL Centre is a multi-disciplinary research centre, bringing together researchers from UCD, TCD, NUIG and Intel, funded by Intel, GE and IDA Ireland. http://www.trilcentre.org.

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Clinically, postural stability during quiet standing is commonly examined to assess falls risk [6-8]. Different test conditions – different stance, eyes open/eyes closed, standing on a compliant/firm surface [9-11] – are employed to gain understanding of the underlying causes of balance dysfunction. Assessments such as the 'Berg Balance Scale' or Tinetti's 'Performance Oriented Balance and Mobility Assessment' use a range of test conditions, aiming to provide a holistic measure of balance [6, 12]. While it is established that postural sway increases at reduced stance widths, and for more physically demanding stances [9, 11, 13], the utility of individual stances as falls risk assessments remains to be fully elucidated.

Body-worn accelerometers, attached to the lower back, may also be used to assess movement of the body's centre of mass (COM) [14, 15]. Using this method, root mean square (RMS) acceleration is the traditional measure of postural sway [9, 11]. Centre of pressure (COP) is also commonly assessed using force platforms [1, 16-18], where COP reflects the response of the body to movement of the centre of mass (COM) [19]. COP trajectory and COM acceleration have been reported to be strongly correlated [17].

COM displacement has been assessed using accelerometry previously, using either a double integration method [20-22], or a frequency domain approach [10]. Recently, Palmerini *et al.* [10] derived accelerometer-derived measures of COM displacement which were related to postural sway during mild Parkinson's disease. However, the utility of COM displacement computed using accelerometry in falls risk assessment is not yet established.

In this study, a group of participants, categorised as fallers or non-fallers, performed instrumented quiet standing trials in two different stances. A range of measures of COM displacement were assessed, along with standard measures of accelerometer-derived postural sway, RMS acceleration. This study aimed to identify which parameters, and which stance, best differentiated participants based on falls status.

II. Methods

A. Cohort

A convenience sample of 110 adults aged older than 60 years (57 female; Mean ± standard deviation age: 73.34 ±

5.57 years; Height: 166.40 ± 9.27 cm; Weight: 76.79 ± 14.74 kg) participated in this study. All participants scored 23 or greater on the mini-mental state exam [23], and had never experienced a stroke or suffered from Parkinson's disease. Ethical approval was obtained from the local research ethics committee.

Participants were interviewed by a research nurse trained in geriatrics to establish their falls status. 56 participants were classified as 'fallers' (29 female; age: 73.55 ± 5.43 years); 27 had fallen within one year prior to assessment; 29 had fallen within the previous five years. 54 participants were classified as 'non-fallers' (28 female; age: 73.11 ± 5.75 years), as they had not fallen within the previous five years, and were deemed not to suffer from any known falls risk factors [24].

B. Protocol

Each participant completed a series of instrumented balance assessments. Participants were asked to remove their shoes and to wear disposable non-slip footwear during all trials. Participants were required to stand as still as possible for 35 seconds in the comfortable stance, with their feet approximately hip-width apart, Fig. 1. This was repeated 6 times with one minute rest provided between trials. Participants were also asked to stand as still as possible for 40 seconds in a semi-tandem stance, feet close together with the toe of the dominant foot in line with the heel of the opposite foot, Fig. 1. This was repeated 3 times with one minute rest provided between iterations. During both stances, participants kept their arms relaxed and by their sides and their eyes open, looking straight ahead.

A body-worn inertial sensor (Shimmer, Shimmer research, Dublin, Ireland), containing a tri-axial accelerometer, was attached to the lower back at approximately the level of L4 using surgical tape.

Fig. 1. Test conditions: comfortable stance (left), and semi-tandem stance (right).

C. Data acquisition

Acceleration data were sampled at 102.4 Hz and streamed via Bluetooth to a PC using a custom application developed in BioMOBIUS™, and were subsequently analysed using Matlab 7.10 (The Mathworks Inc., Natick, MA, USA).

D. Data analysis

Acceleration data were band-pass filtered between 0.1-10 Hz, calibrated [25] and the influence of gravity was accounted for [26]. The initial 5 seconds of data were removed, and the subsequent 25 seconds of data were considered for further analysis. Finally, low frequency drift was removed using a second-order polynomial fit [9].

Cumulative horizontal acceleration, *Acc hor*, was calculated using the medial-lateral (ML) and anterior-posterior (AP) acceleration vectors using equation 1.

$$Acc\ hor = \sqrt{Acc\ ML^2 + Acc\ AP^2} \qquad (1)$$

COM displacement (*D*) was then examined by twice integrating the acceleration signal, using a trapezoidal method. To reduce the error associated with integration, low frequency drift was reduced using a second-order polynomial fit and subtracting the mean amplitude of the signal before and after each integration procedure. The signal was also high pass filtered at 0.1 Hz after both integration procedures, to further reduce the integration-related error. Cumulative horizontal displacement, *D hor*, was calculated in the same manner as acceleration, equation 1.

Displacement ML and AP *Range* were also estimated for each trial. Additionally, estimates of ML, AP and cumulative horizontal sway length (SL) and mean sway velocity (SV) were calculated (equation 2 and 3). Where Δ represents the difference in a value between samples.

$$SL\ x = \sum |\Delta D\,x| \ \ldots x = AP, ML, hor \qquad (2)$$

$$SV\ x = \overline{\frac{|\Delta D\ x|}{\Delta Time}} \ \ldots x = AP, ML\ or\ hor \qquad (3)$$

For comparison, RMS acceleration was also examined for the AP, ML and horizontal signals. The mean value of each parameter was examined for each participant under each condition. The association between each parameter and falls status was investigated, to identify parameters which may be beneficial to falls risk assessments. Additionally, the correlation between each measure of COM displacement and each RMS acceleration parameter was investigated to establish whether each measure could add value to a falls risk assessment.

One way analysis of variance (ANOVA) was used to examine the difference in each measure between fallers and non-fallers, and between stance conditions. The correlation between measures of displacement and RMS acceleration were also examined. P-values less than 0.05 were considered to be statistically significant. Data and statistical analyses were conducted using Matlab 7.10 (The Mathworks, Natick, MA, USA).

III. RESULTS

The ages of fallers and non-fallers were compared using one way ANOVA, with no significant difference observed ($p = 0.68$).

All derived parameters of RMS acceleration and estimates of COM displacement were significantly ($p<0.005$) greater for semi-tandem compared with comfortable stance. COM displacement for an example faller (67 years old female) and non-faller (84 years old male) are presented in Fig. 2A for comfortable stance, and Fig. 2B for semi-tandem stance.

Table I. Accelerometer-derived parameters (mean ± standard deviation) for fallers and non-fallers in a comfortable stance, and p-values representing the difference between groups.

Parameter	Non-fallers	Fallers	P
	Comfortable Stance		
Range AP (mm)	19.02±15.35	23.56±19.28	0.000
Range ML (mm)	12.69±8.51	14.40±9.12	0.014
SL AP (mm)	190.26±157.77	234.65±200.81	0.000
SL ML (mm)	125.82±84.51	145.06±93.50	0.005
SL *hor* (mm)	255.04±167.65	310.19±205.89	0.000
SV AP (mm/s)	9.91±7.18	12.29±9.13	0.000
SV ML (mm/s)	6.30±3.84	7.19±4.25	0.005
SV *hor* (mm/s)	12.90±7.63	15.59±9.37	0.000
RMS Acc AP (g)	0.05±0.02	0.06±0.03	0.000
RMS Acc ML (g)	0.03±0.01	0.04±0.01	0.000
RMS Acc *hor* (g)	0.06±0.02	0.07±0.03	0.000
	Semi-tandem stance		
Range AP (mm)	28.20±23.16	34.66±27.68	0.026
Range ML (mm)	32.09±21.19	37.31±26.84	0.039
SL AP (mm)	280.88±226.14	351.84±286.24	0.012
SL ML (mm)	314.34±193.48	369.18±276.90	0.017
SL *hor* (mm)	479.83±271.54	581.08±365.14	0.002
SV AP (mm/s)	14.79±10.29	18.19±13.02	0.012
SV ML (mm/s)	15.50±8.80	18.48±12.60	0.017
SV *hor* (mm/s)	23.71±12.35	28.82±16.61	0.002
RMS Acc AP (g)	0.07±0.03	0.08±0.04	0.007
RMS Acc ML (g)	0.08±0.02	0.09±0.04	0.000
RMS Acc *hor* (g)	0.11±0.03	0.12±0.05	0.000

Results for each sensor-derived parameter are presented in Table I, for fallers and non-fallers. All examined parameters provided significant discrimination between fallers and non-fallers during both stances, Table I. Fallers exhibited significantly greater range of AP and ML displacement, sway length (ML, AP and *hor*), sway velocity (ML, AP and *hor*), and RMS Acc (ML, AP and *hor*).

During comfortable stance, greater AP range of COM displacement was observed relative to ML Range for both fallers and non-fallers, while the converse was observed during semi-tandem stance. P-values were reduced for all parameters of COM displacement for comfortable stance relative to semi-tandem stance.

During comfortable stance, correlations between measures of COM displacement and RMS measures were not greater than r = 0.68 (RMS Acc ML and SL ML), Table II. During semi-tandem stance, correlations between measures of COM displacement and RMS measures were not greater than r = 0.76 (RMS Acc AP and SL AP), Table II.

Table II. Correlations (r) between accelerometer-derived parameters during comfortable and semi-tandem standing. * indicates significant correlations.

	Comfortable Stance			**Semi-tandem**		
	RMS Acc AP	**RMS Acc ML**	**RMS Acc *hor***	**RMS Acc AP**	**RMS Acc ML**	**RMS Acc *hor***
Range AP	0.57 *	0.40 *	0.57 *	0.75 *	0.59 *	0.71 *
Range ML	0.31 *	0.69 *	0.43 *	0.30 *	0.52 *	0.44 *
SL AP	0.56 *	0.37	0.56 *	0.76 *	0.59	0.71 *
SL ML	0.31 *	0.68 *	0.43 *	0.31 *	0.53 *	0.45 *
SL *hor*	0.54 *	0.51 *	0.58 *	0.68 *	0.67 *	0.72 *

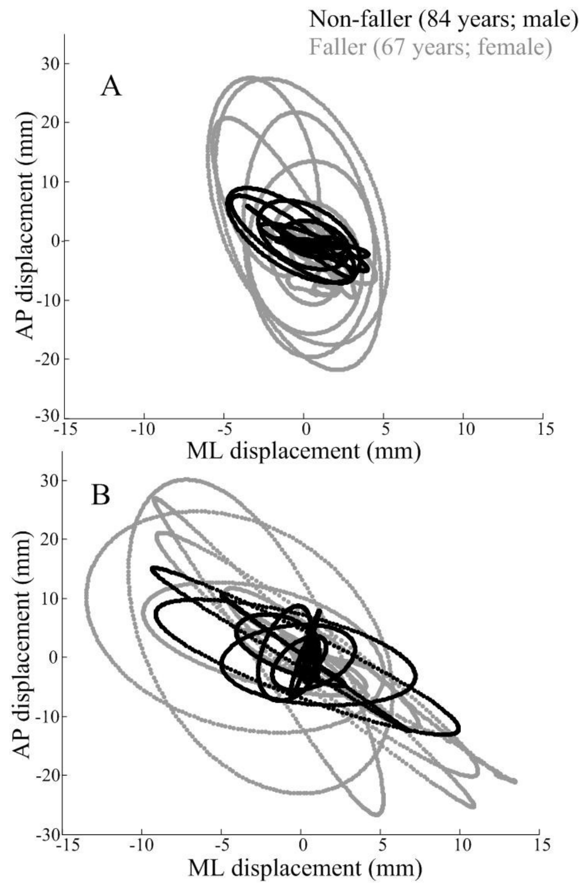

Fig. 2. ML and AP COM displacement for a 67 years old female faller (grey) and an 84 years old male non-faller (black) standing in a comfortable stance (A) and semi-tandem stance (B).

IV. DISCUSSION

This study reports postural sway in a group of older fallers and non-fallers. A range of parameters quantifying COM displacement were derived, along with standard RMS acceleration. Two stance conditions were investigated, a comfortable stance and a more challenging semi-tandem stance. Results indicate that the derived parameters provide significant discrimination of fallers from non-fallers for both stances. Interestingly, improved discrimination was observed during comfortable stance compared with semi-tandem stance, which may have relevance to unsupervised balance assessment.

COM displacement was approximated by twice integrating the acceleration signal obtained from an accelerometer on the lower back. Numerical techniques were implemented to reduce the error associated with integration. Using these procedures, error was reduced but potentially not eliminated. The primary aim of this study was to investigate the utility of these parameters in identifying older adults at risk of falling, hence this method was deemed suitable for comparison across test conditions and participants.

Semi-tandem stance resulted in increased COM displacement and RMS acceleration relative to comfortable stance. Consistent with this finding, Reynolds *et al.* [13] reported increased postural sway, assessed using a motion capture system, for narrow stance relative to feet apart, and for tandem stance relative to both narrow and feet apart stance.

AP sway exceeded ML sway during comfortable stance, likely due to the hip-width stance which may have stabilised ML sway. During semi-tandem stance, the opposite was observed, with increased ML sway range relative to AP sway range. During both stances, ML and AP sway were indicative of falls status.

The reported parameters relating to COM displacement were not highly correlated with the standard RMS acceleration parameters (up to r = 0.76 for semi-tandem and up to r = 0.68 for comfortable stance). Hence, these parameters may add value to falls risk assessments, providing information not captured by RMS acceleration.

Increased correlations were observed during semi-tandem stance relative to comfortable stance were observed for RMS Acc ML and Range AP (r = 0.40 for comfortable stance, r = 0.59 for semi-tandem). Similarly, the correlation between RMS Acc ML and SL AP was notably higher during semi-tandem stance relative to comfortable stance (r = 0.37 for comfortable stance, r = 0.59 for semi-tandem). These results may suggest more interactive control between planes of motion under the more challenging task constraints imposed by semi-tandem stance.

Using a single body-worn accelerometer, the method implemented in this study provides a portable and low-cost balance assessment, which has been shown to be associated with falls risk. The derived parameters relating to COM sway length were significantly discriminative of falls status, while not highly correlated with standard measures of accelerometer-based postural sway. These results indicate that the derived COM displacement parameters provide information complementary to standard measures of accelerometer-based postural sway, and could enhance the accuracy of falls risk assessment. Additionally, both of the stances investigated provided significant discrimination between fallers and non-fallers. Comfortable stance in particular may be suitable for unsupervised, in-home, falls risk monitoring.

References

[1] T. E. Prieto, J. B. Myklebust, R. G. Hoffmann, E. G. Lovett, and B. M. Myklebust, "Measures of postural steadiness: differences between healthy young and elderly adults," *IEEE transactions on bio-medical engineering,* vol. 43, pp. 956-66, Sep 1996.

[2] E. P. Doheny, B. R. Greene, T. Foran, C. Cunningham, C. W. Fan, and R. A. Kenny, "Diurnal variations in the outcomes of instrumented gait and quiet standing balance assessments and their association with falls history," *Physiological measurement,* vol. 33, pp. 361-73, Mar 2012.

[3] G. R. Fernie, C. I. Gryfe, P. J. Holliday, and A. Llewellyn, "The relationship of postural sway in standing to the incidence of falls in geriatric subjects," *Age and ageing,* vol. 11, pp. 11-6, Feb 1982.

[4] World Health Organisation, "WHO Global Report on Falls Prevention in Older Age," 2007.

[5] R. A. Kenny, R. Romero-Ortuno, and L. Cogan, "Falls," *Medicine,* vol. 37, pp. 84-87, 2009.

[6] K. Berg, "Measuring balance in the elderly: preliminary development of an instrument," *Physiother. Canada,* vol. 41, pp. 304-311, 1989.

[7] S. W. Muir, K. Berg, B. Chesworth, N. Klar, and M. Speechley, "Balance impairment as a risk factor for falls in community-dwelling older adults who are high functioning: a prospective study," *Physical therapy,* vol. 90, pp. 338-47, Mar 2010.

[8] B. R. Greene, A. O'Donovan, R. Romero-Ortuno, L. Cogan, C. N. Scanaill, and R. A. Kenny, "Quantitative falls risk assessment using the timed up and go test," *IEEE transactions on bio-medical engineering,* vol. 57, pp. 2918-26, Dec 2010.

[9] M. O'Sullivan, C. Blake, C. Cunningham, G. Boyle, and C. Finucane, "Correlation of accelerometry with clinical balance tests in older fallers and non-fallers," *Age and ageing,* vol. 38, pp. 308-13, May 2009.

[10] L. Palmerini, L. Rocchi, S. Mellone, F. Valzania, and L. Chiari, "Feature selection for accelerometer-based posture analysis in Parkinson's disease," *IEEE transactions on information technology in biomedicine : a publication of the IEEE Engineering in Medicine and Biology Society,* vol. 15, pp. 481-90, May 2011.

[11] G. Kamen, C. Patten, C. D. Du, and S. Sison, "An accelerometry-based system for the assessment of balance and postural sway," *Gerontology,* vol. 44, pp. 40-5, 1998.

[12] M. E. Tinetti, "Performance-oriented assessment of mobility problems in elderly patients," *Journal of the American Geriatrics Society,* vol. 34, pp. 119-26, Feb 1986.

[13] R. F. Reynolds, "The ability to voluntarily control sway reflects the difficulty of the standing task," *Gait & posture,* vol. 31, pp. 78-81, Jan 2010.

[14] M. Mancini and F. B. Horak, "The relevance of clinical balance assessment tools to differentiate balance deficits," *European journal of physical and rehabilitation medicine,* vol. 46, pp. 239-48, Jun 2010.

[15] M. Mancini, F. B. Horak, C. Zampieri, P. Carlson-Kuhta, J. G. Nutt, and L. Chiari, "Trunk accelerometry reveals postural instability in untreated Parkinson's disease," *Parkinsonism & related disorders,* vol. 17, pp. 557-62, Aug 2011.

[16] C. A. Laughton, M. Slavin, K. Katdare, L. Nolan, J. F. Bean, D. C. Kerrigan, E. Phillips, L. A. Lipsitz, and J. J. Collins, "Aging, muscle activity, and balance control: physiologic changes associated with balance impairment," *Gait & posture,* vol. 18, pp. 101-8, Oct 2003.

[17] M. Mancini, C. Zampieri, P. Carlson-Kuhta, L. Chiari, and F. B. Horak, "Anticipatory postural adjustments prior to step initiation are hypometric in untreated Parkinson's disease: an accelerometer-based approach," *European journal of neurology : the official journal of the European Federation of Neurological Societies,* vol. 16, pp. 1028-34, Sep 2009.

[18] S. Pajala, P. Era, M. Koskenvuo, J. Kaprio, T. Tormakangas, and T. Rantanen, "Force platform balance measures as predictors of indoor and outdoor falls in community-dwelling women aged 63-76 years," *The journals of gerontology. Series A, Biological sciences and medical sciences,* vol. 63, pp. 171-8, Feb 2008.

[19] D. A. Winter, "Sagittal plane balance and posture in human walking," *IEEE engineering in medicine and biology magazine : the quarterly magazine of the Engineering in Medicine & Biology Society,* vol. 6, pp. 8-11, 1987.

[20] A. Meichtry, J. Romkes, C. Gobelet, R. Brunner, and R. Muller, "Criterion validity of 3D trunk accelerations to assess external work and power in able-bodied gait," *Gait & posture,* vol. 25, pp. 25-32, Jan 2007.

[21] P. Esser, H. Dawes, J. Collett, and K. Howells, "IMU: inertial sensing of vertical CoM movement," *Journal of biomechanics,* vol. 42, pp. 1578-81, Jul 22 2009.

[22] H. Jeon, S. K. Kim, B. Jeon, and K. S. Park, "Distance estimation from acceleration for quantitative evaluation of Parkinson tremor," *Conference proceedings : ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Conference,* vol. 2011, pp. 393-6, 2011.

[23] M. F. Folstein, S. E. Folstein, and P. R. McHugh, ""Mini-mental state". A practical method for grading the cognitive state of patients for the clinician," *J Psychiatr Res,* vol. 12, pp. 189-98, Nov 1975.

[24] "Summary of the Updated American Geriatrics Society/British Geriatrics Society clinical practice guideline for prevention of falls in older persons," *J Am Geriatr Soc,* vol. 59, pp. 148-57, Jan 2011.

[25] F. Ferraris, U. Grimaldi, and M. Parvis, "Procedure for Effortless In-Field Calibration of Three-Axis Rate Gyros and Accelerometers," *Sensors Mater,* vol. 7, pp. 311-330, 1995.

[26] R. Moe-Nilssen and J. L. Helbostad, "Trunk accelerometry as a measure of balance control during quiet standing," *Gait Posture,* vol. 16, pp. 60-8, Aug 2002.