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# Predicting incident falls: Relationship between postural sway and limits of stability in older adults

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ABSTRACT

*Background:* We have previously shown that objective measurements of postural sway predicts fall risk, although it is currently unknown how limits of stability (LOS) might influence these results.

Research question: How integrated postural sway and LOS measurements predict the risk of incident falls in a population-based sample of older adults.

*Methods::* The sample for this prospective observational study was drawn from the Healthy Ageing Initiative cohort and included data collected between June 2012 and December 2016 for 2396 men and women, all 70 years of age. LOS was compared to postural sway with measurements during eyes-open (EO) and eyes-closed (EC) trials, using the previously validated Wii Force Plate. Fall history was assessed during baseline examination and incident falls were collected during follow-up at 6 and 12 months. Independent predictors of incident falls and additional covariates were investigated using multiple logistic regression models.

*Results::* During follow-up, 337 out of 2396 participants (14%) had experienced a fall. Unadjusted regression models from the EO trial revealed increased fall risk by 6% (OR 1.06, 95% CI 1.02–1.11) per each centimeter squared increase in sway area and by 16% (OR 1.16, 95% CI 1.07–1.25) per 1-unit increase in Sway-Area-to-LOS ratio. Odds ratios were generally lower when analyzing EC trials and only slightly attenuated in fully adjusted models.

*Significance::* Integrating postural sway and LOS parameters provides valid fall risk prediction and a holistic analysis of postural stability. Future work should establish normative values and evaluate clinical utility of these measures.

## 1. Introduction

The world is currently experiencing a demographic shift toward a greater proportion of older adults, in part related to advances in research, medical technology and healthcare (UN, 2016). This trend is however not without concerns, since ageing individuals are predisposed to disabling trauma such as hip fractures (Johnell & Kanis, 2006), that impair their ability to perform daily activities (Osnes et al., 2004). Studies have shown that over 90% of all hip fractures are caused by falls (Hayes et al., 1996), illuminating the need for ways to accurately predict and preferably prevent falls among the increasing number of older adults.

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Fall risk may be influenced by postural stability, also known as the individual ability to maintain the body's center of gravity within the base of support (BOS) during dynamic or static activities (Pickerill & Harter, 2011). We have previously published results revealing that impaired postural stability can increase the risk of incident falls by 75–90% among older adults in the highest quintile of postural sway, measured objectively as center of pressure (COP) oscillations when the sensorimotor system compensates for perceived shifts in the body's center of mass. (Johansson, Nordström, Gustafson, Westling, & Nordström, 2017; Morasso, Spada, & Capra, 1999). These results reinforced the findings of earlier studies (Bergland & Wyller, 2004; Maki, Holliday, & Topper, 1994) by providing population-based data on the COP sway length. However, less is clear regarding the potential interaction between COP sway and limits of stability (LOS) in relation to fall risk. LOS can be defined as to how far an individual is willing to extend their COP relative to their BOS without stepping, slipping or falling (Juras, Slomka, Fredyk, Sobota, & Bacik, 2008). Researchers have shown that the BOS and LOS decrease with age and in individuals suffering from neurological deficits such as Parkinson's disease and multiple sclerosis (Kanekar & Aruin, 2013; King, Judge, & Wolfson, 1994; Mancini, Rocchi, Horak, & Chiari, 2008).

However, previous research may be limited by methodological issues in LOS assessment, and it has been suggested that a low-speed, voluntary, controlled leaning procedure is required for more accurate LOS estimations (Forth, Fiedler, & Paloski, 2011). Such a procedure could potentially be enabled by an assisted LOS assessment protocol, where the participant utilizes hand grips to reduce anxiety of falling and may thus be able to expand the LOS area closer to the physical possibility. Furthermore, only a few studies have investigated the potential implications of individuals' COP sway deviations in relation to their functional LOS (Slobounov, Moss, Slobounova, & Newell, 1998), and no previous study has investigated how the relationship between postural sway area and LOS influences fall risk in a population-based sample. Hypothetically, an integrated COP and LOS parameter could predict fall risk more strongly compared to traditional COP deviation measures, since this integration would also take into account the individual's maximal stability tolerance. Thus, the aim of the current study was to examine how postural sway that is integrated with stability limits, predicts incident falls in a cohort of approximately 2400 community-dwelling older adults.

## 2. Methods

### 2.1. Study sample and ethical approval

The investigated sample was drawn from the Healthy Ageing Initiative (HAI) cohort study, ongoing since June 2012 in Umeå, Sweden, which invites all 70-year-old individuals residing in the Umeå municipality to participate. Eligible participants, drawn from population registers, received written information about the study and were subsequently contacted via telephone. If agreeing to participate, they arrived at a prescheduled visit where they provided written consent and commenced testing. The sample used for this study was based on the first 2396 men and women with complete data on postural stability and prospective fall assessments from the HAI cohort. Data were collected between June 2012 and December 2016. This study was permitted by the Umeå University Research Ethics Committee and followed the principles outlined in the World Medical Association's Declaration of Helsinki.

### 2.2. Assessment of postural sway and limits of stability

COP and LOS data were collected using a Wii Force Plate (WFP; Nintendo, Kyoto, Japan), connected via Bluetooth to a stationary computer. Data were acquired by the custom-written Visual Studio software *Balans-Test* (Göran Westling, Umeå University, Department of Integrative Medical Biology) using WiimoteLib v1.7 (https://wiimotelib.codeplex.com/) by Brian Peek. The WFP contains 4 vertical force sensors, which delivers data at ~60 Hz and our software sampled it at 100 Hz after interpolation. Force signals were then exported to MATLAB R2014b (Mathworks, Inc, Natick, MA, USA), filtered with a 3rd degree Butterworth filter (10 Hz), and finally, down-sampled to 20 Hz.

LOS assessment was initiated with each participant standing stationary on the WFP while maintaining eyes open (EO). They were subsequently introduced to a leaning protocol by a research nurse, who instructed the participants to lean as far as they could from the initial static position in a circular motion during 60 s. The motion direction was chosen by the participant although the research nurse instructed a clockwise direction if the participant seemed unsure on how to begin. From a monitor the participants received visual feedback on their COP excursion from the center while forming the LOS, which also provided the final representation when the trial ended. Participants were instructed to maintain a handhold on a provided bar in front of them and apply horizontal forces throughout the whole LOS-estimation procedure. As surprisingly shown in pilot tests, these forces do not influence the vertical force and the gravitational force on the force plate during LOS assessments. The general rationale behind this approach was to enable a slow-velocity leaning protocol that has been suggested for accurate, elliptical LOS estimations (Forth et al., 2011), while also reducing the participant's potential anxiety of falling when attempting to extend the LOS closer to the possible maximum. Lastly, participants were also instructed to only use ankle joint movement when leaning. A secondary LOS measurement was performed if the participant used hip joint movement for leaning, took a step in any direction or would generally not follow the instructions provided by research nurses. With LOS assessment complete, participants removed the hands from the bar in front of them and conducted one EO trial and one eyes closed (EC) trial during 60 s each, measuring COP sway length in a bipedal quiet stance. They were instructed to avoid body movements, stand relaxed with their arms resting at their sides and maintain an upright position. Measurements were repeated in the event instructions were not followed.

Given the positions of the force sensors, we calculated the COP from the force signals. We constructed convex polygons enclosing the trajectories of the COP (Fig. 1). The polygons were characterized by their area (centimeters squared). As indicators of the participants' behavior, we investigated Sway-Area-to-LOS (SA:LOS, 0–100), i.e., the ratio between the sway area and the LOS, as well

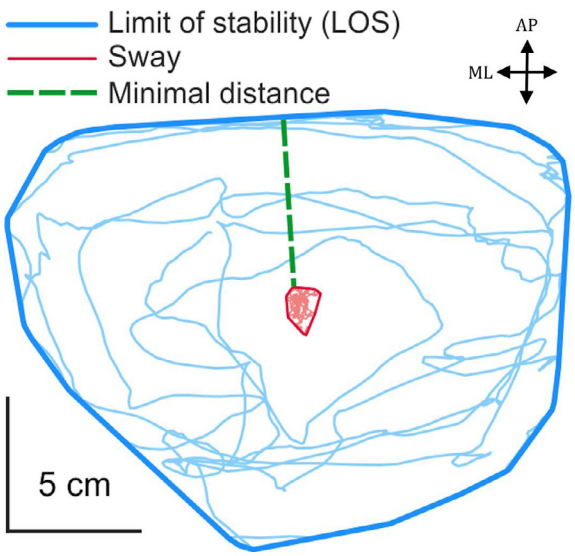


**Fig. 1.** Assessment of Postural sway and LOS parameters. Description of how investigated parameters were calculated. Sway area, in centimeters squared, is represented by the red polygon. The minimal distance to the LOS border (MinD:LOS), in centimeters, is represented by the green dotted line. Sway-Area-to-LOS ratio (SA:LOS), from 0 to 100, is the ratio between the red and blue polygon. The multiple thin, light-blue lines represent participants' center of pressure trace when attempting to establish their LOS.

as Minimal distance between sway area and LOS (MinD:LOS; centimeters). The direction of the MinD:LOS parameter could occur in a 360° angle since it was located wherever the LOS border and the sway area were in closest proximity to each other.

### 2.3. Assessment of physical activity and capacity

Participants wore triaxial accelerometers (GT3X+; Actigraph, Pensacola, FL, USA) during 7 consecutive days following the baseline measurements for physical activity (PA) assessments. Instructions provided to participants and accelerometer settings used have been previously described (Johansson, Nordstrom, & Nordstrom, 2015). Total Moderate-to-Vigorous PA per day was classified as the sum of activity minutes above moderate and vigorous intensity thresholds. Wear time validation protocols defined non-wear time as ≥60 min of consecutive zero activity with a 2-minute spike tolerance. Measurements were excluded from analysis if accelerometer wear time was below 4 days with 10 h per day in total.

Isometric muscle strength was examined using a hydraulic hand dynamometer (Jamar; Patterson Medical, Warrenville, IL, USA) to measure each participant's maximum grip strength in the non-dominant hand. Participants were instructed to maintain the elbow in proximity to the waist and keep the arm at a 90° angle, while compressing the handgrip dynamometer with maximal effort. The maximum value obtained in two consecutive attempts was used in further analyses.

Participants also completed the Timed- Up-and-Go (TUG) test to assess gait ability, lower leg muscle strength and overall functional mobility (Podsiadlo & Richardson, 1991).

### 2.4. Fall data collection

On the day of the examination participants reported retrospective falls that occurred up to 12 months prior to the examination through a questionnaire. Prospective falls were collected by contacting participants at follow-up 6 and 12 months later where a research nurse asked the question: 'During the past 6 months, have you experienced a fall at the same level?' Qualifying retrospective and prospective falls were defined as low-energy incidents where the participant came to rest on the ground unexpectedly by themselves.

### 2.5. Covariates

Height and weight were measured using a gauge (Holtain Limited; Crymych, Dyfed, UK) and a scale (HL 120; Avery Berkel, Fairmont, MN, USA). Body mass index (BMI) was calculated as weight divided by height squared. Participants also took the Mini-Mental-State Examination (MMSE), a common clinical test of cognitive functioning with a maximum score of 30 (Folstein, Folstein, & McHugh, 1975). Participants self-reported current smoking, diabetes, any observed reductions in balance ability and any history of cardiovascular disease (CVD) consisting of myocardial infarctions and stroke.

**Table 1**
Study cohort description and group comparison.

| | | All (n = 2396) | Non-faller (n = 2059) | Faller (n = 337) | p | Men (n = 1224) | Women (n = 1172) | p |
|---|---|---|---|---|---|---|---|---|
| Eyes Open | | | | | | | | |
| | Area ($cm^2$) | 1.96 (2.30) | 1.91 (2.22) | 2.34 (2.73) | **0.007** | 2.01 (1.80) | 1.92 (2.73) | 0.322 |
| | MinD:LOS (cm) | 6.22 (1.45) | 6.25 (1.44) | 6.02 (1.49) | **0.011** | 6.37 (1.48) | 6.05 (1.39) | < **0.001** |
| | SA:LOS Ratio (0–100) | 0.80 (1.13) | 0.77 (1.02) | 1.03 (1.68) | < **0.001** | 0.78 (0.77) | 0.83 (1.42) | 0.203 |
| Eyes Closed | | | | | | | | |
| | Area ($cm^2$) | 5.23 (5.23) | 5.05 (4.81) | 6.32 (7.18) | **0.002** | 6.13 (5.73) | 4.28 (4.45) | < **0.001** |
| | MinD:LOS (cm) | 5.33 (1.57) | 5.37 (1.55) | 5.08 (1.64) | **0.003** | 5.33 (1.64) | 5.33 (1.49) | 0.996 |
| | SA:LOS Ratio (0–100) | 2.14 (2.52) | 2.04 (2.25) | 2.73 (3.75) | **0.002** | 2.39 (2.58) | 1.87 (2.43) | < **0.001** |
| Women (%) | | 48.91 | 48.03 | 54.30 | **0.033** | – | – | – |
| Smoker, yes (%) | | 5.93 | 6.08 | 5.04 | 0.456 | 4.99 | 6.92 | **0.045** |
| BMI ($kg/height^2$) | | 26.46 (4.15) | 26.36 (4.10) | 27.07 (4.44) | **0.006** | 26.75 (3.68) | 26.15 (4.58) | < **0.001** |
| Height (cm) | | 170.20 (8.98) | 170.32 (8.93) | 169.45 (9.21) | 0.099 | 176.70 (6.31) | 163.40 (5.74) | < 0.001 |
| Weight (kg) | | 76.84 (14.29) | 76.67 (14.18) | 77.93 (14.91) | 0.133 | 83.54 (12.30) | 69.85 (12.79) | < **0.001** |
| CVD, yes (%) | | 9.79 | 9.41 | 12.17 | 0.114 | 14.66 | 4.71 | < **0.001** |
| Diabetes, yes (%) | | 8.22 | 7.83 | 10.61 | 0.089 | 10.15 | 6.21 | **0.001** |
| MMSE Score (n) | | 28.55 (1.54) | 28.53 (1.54) | 28.62 (1.55) | 0.321 | 28.42 (1.62) | 28.68 (1.44) | < **0.001** |
| Total MVPA (min/day) | | 33.55 (25.70) | 33.69 (25.46) | 32.65 (27.13) | 0.512 | 35.59 (27.43) | 31.44 (23.60) | < **0.001** |
| Achieving 150 min MVPA/week (%)[a] | | 65.82 | 65.86 | 65.58 | 0.920 | 68.46 | 63.05 | **0.005** |
| Gripstrength (kg) | | 34.69 (10.90) | 34.98 (10.89) | 32.90 (10.82) | **0.001** | 43.43 (7.42) | 25.54 (4.70) | < **0.001** |
| TUG time (s) | | 9.93 (2.24) | 9.85 (2.08) | 10.39 (3.00) | **0.002** | 9.91 (2.04) | 9.95 (2.43) | 0.632 |
| Experiencing impaired balance, yes (%) | | 25.35 | 23.79 | 34.85 | < **0.001** | 20.13 | 30.80 | < **0.001** |
| Previous fall, yes (%) | | 30.92 | 29.33 | 40.61 | < **0.001** | 22.15 | 40.07 | < **0.001** |
| Fallen last year, yes (%) | | 10.24 | 8.58 | 20.30 | < **0.001** | 7.72 | 12.86 | < **0.001** |

Data are presented as means (standard deviation) or in percentages. All participants were 70 years of age at the time of measurement, thus listing age as a parameter was deemed redundant.
MinD:LOS = Minimal Distance to Limit of Stability, SA:LOS = Sway-Area-to-LOS, CVD = Cardiovascular Disease, MMSE = Mini-Mental State Examination, MVPA = Moderate-to-Vigorous Physical Activity, TUG = Timed-Up-and-Go
Boldface indicates statistical significance ($p < .05$) in non-faller vs. faller and men vs. women comparisons
[a] Based on WHO criteria for minimum amount of recommended PA

### 2.6. Statistical analysis

Means ± standard deviations were used to present descriptive data and the Students *t*-test was additionally used to detect potential statistically significant differences between fallers vs. non-fallers and men vs. women respectively (Table 1). Pearson's Chi-squared test was used when investigating dichotomous variables. Multiple logistic regressions models were used to investigate independent predictors of incident falls, presented by odds ratios (OR) and 95% confidence intervals (CI). The first model contained unadjusted OR:s for investigated balance variables in relation to incident falls. The second model was additionally adjusted for sex, BMI, history of CVD and diabetes, TUG test time, MMSE score and current smoking status. The third and final model was further adjusted by moderate-to-vigorous PA (MVPA) per day, maximal grip strength and retrospective falls 12 months prior to baseline measurements. All analyses were performed with Stata software version 13.1 (StataCorp, College Station, TX, USA)

## 3. Results

### 3.1. Study cohort data

In total, 337 (14.1%) participants reported at least one incident fall during follow up at 6 and 12 months. Among these fallers, 20.3% also reported having fallen prior to baseline measurements, compared to 8.6% among the non-fallers ($p < .001$; Table 1). Incident falls were additionally more common among women compared to men ($p = .033$). Furthermore, participants with incident falls had higher BMI ($p = .006$), lower muscle strength ($p < .001$) and worse TUG test performance ($p = .002$), as compared to non-fallers. No significant differences were detected when comparing smoking, history of CVD and diabetes, MMSE score and parameters of PA between fallers and non-fallers (Table 1).

### 3.2. Postural sway relative to assisted stability limits

In the EO trials, total sway area was on average 23% larger among fallers ($p = .007$), while the MinD:LOS was reduced by 4% ($p = .011$), as compared to non-fallers (Table 1). Fallers also showed a 34% higher SA:LOS ratio compared to non-fallers ($p < .001$). Similarly, during EC trials fallers showed a 25% larger sway area, 6% decreased MinD:LOS and 34% higher SA:LOS ratio as compared to non-fallers ($p < .01$ for all; Table 1).

Analyses of the EO trial also revealed that women had 5% decreased MinD:LOS ($p < .001$) compared to men, while there were no

**Table 2**
Postural sway and LOS parameters as independent predictors of incident falls.

| | | Model 1 (unadjusted) | Model 2 | Model 3 |
|---|---|---|---|---|
| Eyes Open | | | | |
| | Area | **1.06 (1.02–1.11)** | **1.06 (1.01–1.10)** | **1.06 (1.01–1.11)** |
| | MinD:LOS | **0.90 (0.83–0.97)** | 0.95 (0.87–1.03) | 0.93 (0.85–1.02) |
| | SA:LOS Ratio | **1.16 (1.07–1.25)** | **1.13 (1.03–1.23)** | **1.12 (1.03–1.23)** |
| Eyes Closed | | | | |
| | Area | **1.04 (1.02–1.06)** | **1.03 (1.01–1.05)** | **1.04 (1.01–1.06)** |
| | MinD:LOS | **0.89 (0.83–0.96)** | 0.93 (0.86–1.01) | **0.92 (0.84–1.00)** |
| | SA:LOS Ratio | **1.09 (1.05–1.13)** | **1.07 (1.02–1.11)** | **1.07 (1.02–1.12)** |

Model 1 included postural sway and LOS parameters only. Model 2 further included adjustment for sex, BMI, CVD, TUG, previous diabetes, MMSE score and smoking. Model 3, the fully adjusted model, additionally included MVPA per day, grip strength and retrospective falls prior to baseline measurements. Bold font indicates statistical significance at the $P < .05$ level.

significant differences in postural sway area and SA:LOS ratio (Table 1). The EC trial revealed opposite results, with men having on average 43% larger postural sway area and 28% increased SA:LOS ratio compared to women ($p < .001$ for all), while no significant difference was detected in MinD:LOS comparison (Table 1).

### 3.3. Independent prediction of incident falls

Unadjusted regression analyses (model 1) of the EO trial revealed increased odds of falling by 6% for each $cm^2$ increase in sway area (odds ratio [OR] 1.06, 95% confidence interval [CI] 1.02–1.11), and by 16% per 1-unit increase in SA:LOS ratio (OR 1.16, 95% CI 1.07–1.25; Table 2). Furthermore, each cm increase in MinD:LOS decreased the odds of falling by 10% (OR 0.90, 95% CI 0.83–0.97). The odds ratios for incident falls relative to sway area and SA:LOS ratio were slightly attenuated in model 2, and relatively unchanged in the fully adjusted model, while MinD:LOS no longer significantly predicted incident falls (Table 2).

Odds ratios for falling relative to investigated parameters were generally weaker in the EC trial compared to the EO trial. In the unadjusted model, 1-unit increments in sway area and SA:LOS ratio increased the odds for a fall by 4% (OR 1.04, 95% CI 1.02–1.06) and 9% (OR 1.09, 95% CI 1.05–1.13) respectively (Table 2). Increasing MinD:LOS by 1 cm reduced the odds for a fall by 11% (OR 0.89, 95% CI 0.83–0.96). Similar to data from the EO trial, odds ratios for incident falls relative to investigated balance parameters changed only marginally in model 2 and in the fully adjusted model (Table 2).

Several covariates also independently predicted incident falls in the final, fully adjusted model. From the EO trial, the odds of falling was 4% higher per 1-unit increase in BMI (OR:s 1.04, $p < .05$ for all), 10% higher per 1-unit increase in MMSE score (OR:s 1.10, $p < .05$ for all), 2% lower per 1-unit increase in grip strength (OR:s 0.98, $p < .05$ for all) and more than twice as high in participants reporting falling in the previous year (OR:s 2.23–2.24, $p < .001$ for all). Odds ratios for incident falls relative to investigated covariates were similar in the EC trial (data not shown).

## 4. Discussion

The results from the current study revealed an association between incident falls and impaired postural stability relative to participants' assisted LOS and fall-related safety margins. The investigated balance parameters independently predicted incident falls, even after adjusting for a rich set of covariates, indicating the importance of considering the individual's LOS when determining fall risk.

We provide novel data on fall risk prediction by investigating objective measures of postural stability integrated with assisted stability limits in a population-based sample of roughly 2400 participants. To our knowledge, very few studies have examined similar parameters as were investigated in the current study, and previous research may also be limited by using time-to-boundary protocol in LOS estimations (Forth et al., 2011). It is however still plausible that the measured LOS area is smaller than some participants' "true" LOS area due to a perceived risk of falling, despite using hand support.

Previous studies have reported that older age may negatively affect the ratio between sway area and LOS, although these studies are limited by a small number of participants investigated with no evaluation of fall risk (Kilby, Slobounov, & Newell, 2014; Slobounov et al., 1998). Regarding stability limits and fall risk, most studies have either investigated study samples with neurological deficits or used a retrospective study design (Faraldo-Garcia et al., 2016; Kanekar & Aruin, 2013; King et al., 1994; Mancini et al., 2008). The current study expands upon the current knowledge by providing integrated postural sway and LOS data with regards to incident falls, from a relatively healthy, population-based cohort of older individuals.

Postural stability measures of interest in this study involved total postural sway area, minimal distance between sway area and the LOS border, as well as the ratio between the postural sway area polygon and the LOS polygon. Although all measures predicted incident falls in the unadjusted model from EO and EC trials, analyzing minimal distances between polygons and fall risk resulted in non-significant odds ratios in adjusted models. There is a possibility that the minimal distance parameter is largely influenced by inter-individual variability when establishing the sway area polygon. The ratio measure between sway area and LOS polygons might be more robust in this regard, and similar parameters have received previous research interest (Slobounov et al., 1998).

However, it remains unclear whether there is an advantage of combined COP and LOS measurements over regular COP measurements in predicting fall risk. There was a trend in our regression models where the combined COP and LOS variable produced stronger odds ratios for incident falls, although this needs to be further explored and statistically confirmed. Furthermore, there was only a relatively small fall risk increase by roughly 0.1 in odds ratio per unit change in the integrated COP and LOS parameter, a change that can be considered rather substantial in the context that the mean SA:LOS ratio value was 0.8–2.1 for the whole study sample. Based on these results, the rationale for involving such a parameter in fall risk screening remains unclear. Still, we believe there are merits in using measurements of postural stability in a bipedal, quiet stance, since these types of tests provide an objective measurement that is easily standardized and feasible for older adults to perform. As such, the relationship between COP and LOS measurements requires further elucidation, and others have argued that the addition of LOS estimation enables quantification of instantaneous postural stability which is important for fall risk prediction (Kilby et al., 2014).

Comparing postural sway and LOS estimations between men and women revealed some discrepancies between EO and EC trials. Men expressed a significantly larger sway area in the EC trial only, while other studies have reported significant sex differences in postural stability also during EO status (Era et al., 2006; Sullivan, Rose, Rohlfing, & Pfefferbaum, 2009). One possible explanation behind this discrepancy is the innate difference between the parameters; we report the sway area, expressed in centimeters squared, which is the resulting geometric form of combined anterio-posterior and medio-lateral COP deviations, while many previous studies report the continuous COP path length. Men also expressed a significantly increased ratio between sway area and LOS during the EC trial, compared to women, indicating reduced postural stability relative to safety margins. However this did not accurately reflect upon the sex differences in fall rates shown in the current study, where women were generally more prone to falling compared to men.

Interestingly, participants who sustained falls within 12 months prior to the examination were more than twice as likely to experience new prospective falls compared to participants with no history of falling. This self-reported fall assessment was the strongest predictor for experiencing new falls in the current study and it reaffirms the importance of collecting fall histories when examining older individuals at potential risk. Our findings are supported by previous studies where assessment of fall frequency history predicted the incidence of hip fractures (Faulkner et al., 2009; Nguyen, Pongchaiyakul, Center, Eisman, & Nguyen, 2005), likely to be the consequences of falling (Hayes et al., 1996).

This study has several strengths. We followed up on falls prospectively, a clear advantage over retrospective designs when predicting fall risk from baseline measurements (Howcroft, Kofman, & Lemaire, 2013; Moe-Nilssen, Nordin, & Lundin-Olsson, 2008). Furthermore, we measured postural sway and stability limits objectively, thus avoiding subjective scoring systems and reducing test performance variability (Visser, Carpenter, van der Kooij, & Bloem, 2008). Also, our regression models were adjusted with a rich set of covariates, including previous falls, objective physical activity, cognitive ability and muscle strength. The latter have been shown to impact LOS measurements (Melzer, Benjuya, Kaplanski, & Alexander, 2009), although it did not severely influence the relationship between investigated balance parameters and falls in the current study.

There are also some limitations to consider. First, we did not have access to medication use, such as antidepressants, nor did we collect data on neurological deficits or musculoskeletal conditions; these data would have been valuable to analyze in relation to fall risk. Second, we included participants at the exact age of 70 only, thus limiting generalizability of results to other age groups. Additionally, our assisted LOS protocol may limit the generalizability of our results to the findings of previous studies who included conventional functional LOS assessments. Third, we followed up on falls 6 and 12 months after the examination and the total fall rate was 14%, which is lower than the average of 30–35% reported in a previous meta-analysis (Bloch et al., 2010). It is possible that the follow-up periods may have led to recollection difficulties of falls among some participants. However, it can be argued that the study cohort is healthier and less prone to falling compared to other geriatric populations due to the younger and homogenous age range, and also since 66% of participants achieved at least 150 min of moderate PA per week.

## 5. Conclusion

Postural sway in relation to assisted stability limits appears to be a valid predictor of incident falls, even after adjusting for multiple covariates. The addition and integration of LOS assessment to regular measurements of postural sway could potentially improve fall risk prediction, although this needs to be further investigated. Future work should focus on establishing normative values and evaluate clinical utility of these parameters.

## Conflict of interest statement

Declarations of interest: none

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.04.004.

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