

1 **Title Page (Original research)**

2 **Title:**

3 Fall assessment in healthy older adults: Approach using rambling-trembling decomposition method

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Abstract

Background: This study explored useful indices of potential fall risk in healthy older adults based on comprehensive clinical and simple quantitative posturographic measurements.

Methods: A total of 64 community-dwelling older adults aged ≥ 65 years were classified into fallers and non-fallers based on a previous fall history. After excluding two participants due to missing data, 16 and 46 participants were included in the faller and non-faller groups, respectively. We conducted major clinical measurements, including timed up and go test, 10-meter walk test, functional reach test, one-leg stand test, isometric muscle strength tests, open-close stepping test, and sit-to-stand test. For quantitative posturographic measurements, participants performed standing tasks with their eyes open and closed. In the standing tasks, the time series of the center of pressure in the anteroposterior and mediolateral directions during standing was decomposed into rambling and trembling components to evaluate postural control in detail, separately. The mean velocity and root mean square of the center of pressure, rambling, and trembling were calculated and compared between fallers and non-fallers.

Findings: A significant fall-related difference was found only in the mean velocity of the rambling in the anteroposterior direction; fallers displayed greater values than non-fallers, especially while standing with their eyes closed.

Interpretation: The clinical measures failed to distinguish differences in fall risk, whereas the rambling component in the anteroposterior direction could detect substantial differences. The mean velocity of the

42 rambling component could be useful as a sensitive screening biomarker for potential fall risks in healthy

43 older adults.

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45 **Keywords:** Quiet standing; Fall; Older adults; Rambling; Trembling

1. Introduction

Falls in community-dwelling older adults are a serious problem, and approximately 30% of individuals older than age 65 experience falls at least once each year, increasing to 50% in those older than age 80 (Rubenstein, 2006; Swift and Iliffe, 2014). The risk factors for falls have been widely explored in older adults, and several functions such as balance, muscle strength, and gait have been identified as strong risk factors for falls (Hausdorff et al., 2001; Tinetti and Kumar, 2010). It is also possible that multiple factors rather than a single fixed factor may cause falls in older adults. Early detection of potential fall risk in healthy older adults is crucial for preventing fall-induced injuries and subsequent functional decline.

Various screening tools have been established to detect fall risk in older adults (Barker, 2014). In particular, quick and easy clinical measurements such as the timed up and go test are popular as useful fall-assessment batteries (Viccaro et al., 2011). However, their limited ability to predict future falls has been previously demonstrated; for instance, several studies have shown that the timed up and go test is unable to predict falls (Lindsay et al., 2004; Silva et al., 2022), and a systematic review concluded that its cut-off values vary widely among studies and that such simple clinical measurements are inadequate for predicting future falls (Meekes et al., 2021). Clinical measurements may be limited because the postural control system involves the complex integration and coordination of multiple body systems (Horak, 1987; Meekes et al., 2021), and additional assessment tools are required to address this issue. A recent systematic review reported that future fall risk can be assessed by simple quantitative posturographic tests with eyes open

(EO) and closed (EC) rather than clinical measurements and that center of pressure (CoP) measures such as anteroposterior CoP velocity would be good indices to predict fall risk (Quijoux et al., 2020).

In addition to the CoP measures, the rambling-trembling decomposition of the CoP time series during quiet standing has been developed to evaluate postural control in detail (Zatsiorsky and Duarte, 1999, 2000).

In this analysis, the CoP trajectory was decomposed into rambling (Rm) and trembling (Tr) components.

Rm approximates the trajectory of the CoP (the point of application of the resultant vertical force acting on the body), computed as an interpolation of instantaneous equilibrium points (i.e., the points at which the

horizontal force is zero). Tr represents the oscillation of the body to moving equilibrium reference,

computed as the difference between the CoP and Rm. The Rm component was viewed as reflecting

supraspinal processes, whereas the Tr component was viewed as primarily a reflection of peripheral

mechanics, such as the spinal reflex or mechanical properties (Zatsiorsky and Duarte, 1999, 2000). In a

recent study using this decomposition technique, simulated somatosensory deficits in healthy young adults

predominantly altered the Rm component of postural sway while standing (Gerber et al., 2022). Similar

observations, that is large alterations in the Rm component, were also observed in a study exploring age-

related changes (Sarabon et al., 2013). Failure to adjust the Rm component may prevent an appropriate

response of the body to the perturbations encountered in daily life, resulting in falls. Therefore, the Rm

component of the CoP time series may be a useful index for assessing the potential fall risk in healthy older

adults. However, it remains unclear whether the Rm-Tr decomposition is a useful method for assessing fall

risk.

Therefore, this study aimed to explore useful indices to assess potential fall risk in healthy older adults.

This exploratory study evaluated the fall risk based on a previous history of falls (Ambrose et al., 2013;

Tinetti and Kumar, 2010), and used several types of clinical and simple quantitative posturographic

measurements for fall assessments. We expected that indices using simple quiet-standing tasks, especially

the Rm component of postural sway, would be useful for assessing fall risk in healthy older adults.

2. Methodology

2.1 Participants

A total of 64 community-dwelling older adults aged ≥ 65 years participated in the study. For the recruitment process, we sent a recruitment letter to all older adults who had participated in another physical fitness test in Kyoto city who met the following inclusion criteria to ask whether they would like to participate: (1) individuals without neurological disorders or musculoskeletal injuries, (2) individuals who could stand still without any assistance for more than one minute, and (3) individuals without cognitive impairments that would prevent accurate performance of instructions (Mini Mental State Examination score > 23 points (Kochhann et al., 2010)). This study included older adults who indicated their willingness to participate by replying to the letter. Written informed consent was obtained from all participants and all protocols were approved by the Research Ethics Committee of Kyoto University

(R1746). The research design is shown as a flowchart in Figure 1.

We asked the participants whether they had experienced falls in the 12 months prior to the experiments. A fall was defined as an event in which an individual unintentionally comes to rest on the floor, ground, or other lower level, regardless of whether an injury occurred (Maki, 1997). Participants were classified into two groups based on fall history within the last 12 months. Participants who had experienced at least one fall were classified as fallers, and those who had not experienced a fall were classified as non-fallers. Sixteen participants were included in fallers and 46 participants were included in non-fallers. The physical characteristics of both groups are shown in Table 1. Two participants were excluded due to missing fall history data, and no participants with falls had serious injuries due to falls.

2.2 Clinical Measurements

We conducted the following clinical measurements at random: timed up and go test, 10-meter walk test, functional reach test, one-leg stand test, isometric muscle strength tests, open-close stepping test, and sit-to-stand test. All clinical measures were performed with shoes on and evaluated by several physical therapists with adequate skills and knowledge.

The timed up and go test (Viccaro et al., 2011) and the 10-meter walk test (Tyson and Connell, 2009) were used to assess functional mobility. In the timed up and go test, the participants were instructed to perform the following tasks as quickly as possible after a command of “go”: stand up from a sitting

position, walk to a mark 3 meters away, turn around, walk back, and sit down. Time was measured using a stopwatch that was started when the instruction to “go” was given and stopped when the back of the participant was against the back of the chair after sitting down. In the 10-meter walk test, participants were asked to walk at a comfortable speed to a landmark that was 14 meters ahead. Using a stopwatch, we measured the time taken to walk 10 meters excluding the first and last 2 meters and evaluated the gait speed (m/s). Each measurement was performed twice, and the minimum time was recorded.

Functional reach test (Duncan et al., 1990) and one-leg stand test (Maki et al., 1994) were also conducted to assess dynamic and static balance abilities. In the functional reach test, participants stood with their right shoulder flexed at 90° and reached forward as far as possible. The test was conducted once and the maximum distance was evaluated. In the one-leg stand test, we asked the participants to stand on any leg for as long as possible with both arms on their hips. The test was performed with their eyes closed for a maximum of 3 minutes. Using a stopwatch, we measured the time required for the supporting foot to rise from and touch the ground. The test was performed twice, and the longest time was recorded.

Isometric muscle strength tests of the knee extensors and hip abductors were conducted to assess the muscle strength of the lower limbs. In the knee extensor test, the maximum strength of the right knee extensors was measured using an isometric dynamometer (Isoforce FT-330; OG GIKEN Co., Okayama, Japan). The participants were seated with the knee flexed at 60° and a sensor pad was placed 26 cm from the knee joint to measure the maximal isometric strength of knee extension. In the hip abductor test,

maximal isometric strength of the right hip abductor was measured using a handheld dynamometer (Mobie; Sakai Medical Co., Tokyo, Japan). The participants were asked to produce the maximal isometric strength of hip abduction in the supine position. Both strength tests were performed twice, and the maximal forces were assessed. Torque (Nm/kg), computed using the maximal force (N), lever arm (m), and body weight (kg), was used for further analysis.

To comprehensively evaluate physical function, we also included the open–close stepping test as a measurement of agility (Yoshinaka et al., 2018) and the sit–to–stand test as an indicator of lower limb function (Alcazar et al., 2018; Bohannon et al., 2010). In the open–close stepping test, participants were seated in a chair and both feet were placed inside two 30-cm-wide lines. We asked them to open and close both feet as quickly as possible in 20 seconds. The number of open–close steps was counted. In sit–to–stand test, we instructed the participants to repeatedly stand up from and sit down on a chair as quickly as possible, and the number of sit-to-stand repetitions in 30 seconds was recorded. In both tests, we confirmed the measurement time of 20 or 30 seconds using a stopwatch and counted the number of times. The tests were performed once.

2.3 Quantitative Posturographic Measurements

Participants stood quietly on a force plate (Kistler Japan Co., Ltd., Tokyo, Japan) for 60 seconds with their feet together and their arms crossed over their chests. The two standing tasks with EO and EC

were performed at random. In the EO condition, participants stood while looking at a sign placed at eye level on a wall approximately 3 meters away, while in the EC condition, they closed their eyes after looking at the sign on the wall.

Three force and moment components were recorded at 1kHz, and low-pass filtered at 10 Hz using a fourth-order zero-lag Butterworth filter. For further analysis, we removed the data for the first 5 seconds. Additionally, we computed the Rm and Tr trajectories using the decomposition of CoP in the anteroposterior (AP) and mediolateral (ML) directions (Zatsiorsky and Duarte, 2000). Briefly, we first identified instantaneous equilibrium points (IEPs), which were defined as the CoP coordinates when the ground reaction force in the AP direction (F_{AP}) was zero. To estimate the Rm trajectory, we computed the cubic spline interpolation of the IEP coordinates. The trajectory of the Tr was evaluated based on the deviation of the CoP from the Rm trajectory. The typical CoP, Rm, and Tr trajectories in the AP direction are shown in Figure 2. After obtaining the Rm and Tr trajectories, we removed the first and last 1-s of the data to eliminate edge effects (Yamagata et al., 2019a; Yamagata et al., 2019b). To assess postural control during standing, the root mean square (RMS) and mean velocity (MV) of the CoP (CoP_rms and CoP_mv), Rm (Rm_rms and Rm_mv), and Tr trajectories (Tr_rms and Tr_mv) in the AP and ML directions were computed and compared between fallers and non-fallers.

2.4 Statistical Analysis

Prior to the statistical analyses, we tested the assumptions of normality. Because the Kolmogorov–Smirnov tests showed that some indices deviated from the normal distribution, this study mainly performed non-parametric tests. For the homogeneity of variances and independence of observations, we confirmed that equal variances could be assumed in all indices using the Levene’s test and the indices were not dependent on one another.

To explore the effects of group (faller and non-faller) and vision (EO and EC) on CoP-, Rm-, and Tr-related measures, we performed analyses of variance for split-plot factorial designs. We used the variance analyses because there were no non-parametric alternatives. When significant interactions were detected, post-hoc comparisons were separately performed to explore fall-related differences in EO and EC conditions. To test whether the indices of clinical measurements differed between fallers and non-fallers, we performed Mann-Whitney U-tests to compare the values between groups. The significance level was set at 0.05, and Bonferroni corrections were applied for post-hoc comparisons.

3. Results

3.1 Physical characteristics and clinical measurement indices

The physical characteristics of both groups are shown in Table 1. There were no significant differences in age, height, or mass between the groups. No significant differences were found in any of the clinical measurement indices between the non-fallers and fallers (Table 2).

3.2 Posturographic measurement indices

The typical time profiles of the CoP, Rm, and Tr in representative non-fallers and fallers are shown in the Appendix. The results for CoP_mv, Rm_mv, and Tr_mv are shown in Figure 3. In the CoP_mv and Tr_mv, significant *Vision* effects were found in the AP (CoP_mv $F(1, 60) = 39.8; p < 0.001; \eta^2 = 0.40$, Tr_mv $F(1, 60) = 41.9, p < 0.001; \eta^2 = 0.41$) and ML directions (CoP_mv $F(1, 60) = 27.7; p < 0.001; \eta^2 = 0.33$, Tr_mv $F(1, 60) = 27.1, p < 0.001; \eta^2 = 0.32$), and the indices in the EC condition were significantly greater than those in the EO condition. Significant *Vision* effects were also found in Rm_mv in the ML direction ($F(1, 60) = 24.1, p < 0.001; \eta^2 = 0.30$). However, no significant *Group* effect or interaction was found. For Rm_mv in the AP direction, there were significant effects of *Group* ($F(1, 60) = 6.5, p < 0.01; \eta^2 = 0.11$) and *Vision* ($F(1, 60) = 23.7, p < 0.001; \eta^2 = 0.31$). A significant *Group* x *Vision* interaction was also observed ($F(1, 60) = 4.7, p < 0.05; \eta^2 = 0.10$). The Rm_mv in fallers was significantly higher than that in non-fallers, especially under the EC condition ($p < 0.05; r = 0.30$).

Figure 4 presents the results of the RMS-related indices. Regarding CoP_rms and Rm_rms in the AP direction, a significant *Vision* effect was found (CoP_rms $F(1, 60) = 29.3; p < 0.001; \eta^2 = 0.33$, Rm_rms $F(1, 60) = 7.8; p < 0.01; \eta^2 = 0.12$); however, no *Group* effects were found. We found a significant *Group* x *Vision* interaction in CoP_rms in the AP direction ($F(1, 60) = 8.7, p < 0.01; \eta^2 = 0.13$) and Rm_rms ($F(1, 60) = 7.8, p < 0.01; \eta^2 = 0.12$); however, no significant differences between fallers and

non-fallers were found in either the EO or EC conditions. For Tr_rms in the AP direction, a significant *Vision* effect was found ($F(1, 60) = 34.9, p < 0.001; \eta^2 = 0.36$), but no *Group* effect or interaction was observed. In the ML direction, we did not find effects of *Vision* and *Group* effect in CoP_rms and Rm_rms, but significant *Vision* effect was found in Tr_rms ($F(1, 60) = 42.6, p < 0.001; \eta^2 = 0.43$). No interaction was observed in indices in the ML direction.

4. Discussion

This study aimed to explore useful indices to assess potential fall risk in healthy older adults. We did not find any differences in clinical measures or CoP- and Tr-related measures in the AP and ML directions between fallers and non-fallers. No fall-related difference was found in Rm-related measures in the ML direction either; however, a group effect was found in the mean velocity of the Rm component in the AP direction, with fallers displaying significantly greater values than non-fallers. The results partly supported our hypothesis that posturographic measurements (especially the Rm component of postural sway) would be useful for assessing fall risk in healthy older adults. To the best of our knowledge, this is the first study to demonstrate that the Rm component is associated with the fall risk and to indicate that the rambling-trembling decomposition method can be used as a new fall assessment measure.

4.1 The usefulness of the rambling-trembling decomposition method

The CoP velocity did not distinguish fallers and non-fallers, whereas the Rm velocity in the AP direction decomposed by the CoP time series was higher in fallers than in non-fallers. Additionally, such a difference increased while standing with the eyes closed. In a previous study on the simulated somatosensory deficit by foam pads, it was revealed that in the AP direction, the Rm was increased by the somatosensory deficit more than the CoP and Tr during standing (Gerber et al., 2022). Such a substantial increase in the Rm was also observed when participants stood on a smaller base of support (Mochizuki et al., 2006) and participants attempted to keep the CoP or head orientation within a smaller target during standing (Danna-Dos-Santos et al., 2008). These previous findings implied that the Rm would increase when conscious or voluntary efforts were made to control postural sway and support the idea that the Rm reflects central control. In this study, Rm alteration in a normal standing task was observed in the AP direction even in healthy older adults if they have a fall risk, implying that their supraspinal control may have been changed due to the potential fall risk. In particular, similar to postural strategies while standing on unstable ground (Mochizuki et al., 2006) and in individuals with somatosensory deficits (Gerber et al., 2022), healthy older adults with a high fall risk may use the central nervous system to search for a limit of stability by constantly moving their CoP or shifting their equilibrium point in the AP direction, even during quiet standing. While it remains unclear how much the Rm reflects complex supraspinal processes, Rm calculations computed from easy posturographic measurements may be useful as screening tools for potential fall risk in healthy adults at an early stage if force plate measurements are available.

No significant differences were found in the Tr-related indices in both directions between fallers and non-fallers. Earlier studies have observed alterations in the Tr as well as the Rm components with aging (Degani et al., 2017) and disease (Costa et al., 2022), slightly different from our findings. Tr has been viewed primarily as a reflection of peripheral mechanics, such as the mechanical properties of the effectors and spinal reflex loops (Zatsiorsky and Duarte, 2000), and is changed by peripheral factors such as muscle co-activation (Yamagata et al., 2019a) or muscle weakness. Previous differences in the Tr component might have been caused by age- and disease-related alterations in peripheral factors, such as muscle mechanical properties. In this study, no statistically significant differences in muscle strength were found between fallers and non-fallers (Table 2), although muscle dysfunction or weakness is a major factor in fall risk (Tinetti and Kumar, 2010). Alterations in the Tr component may not have been found because fallers and non-fallers used similar peripheral mechanics during standing. The rambling-trembling decomposition of the CoP time series would provide a deeper understanding of postural control mechanisms, and periodic evaluation using this technique may also be useful in determining the effectiveness of interventions, in addition to screening for fall risk, in clinical practice. Future studies are warranted to clarify whether this measure could be useful for a broader assessment.

4.2 The necessity of comprehensive measurements

A fall-related difference was observed in the MV of the Rm component in the AP direction, whereas

no difference was observed in the RMS of Rm component (Figures 3 and 4). Similar results have been found in previous studies; MV has been reported to be better at detecting age-induced changes in postural control than RMS (Maki et al., 1990; Prieto et al., 1996). A systematic review has also shown that MV reflects fall risk better than RMS (Quijoux et al., 2020), and MV indices may alter first owing to postural disability and fall risk, followed by RMS indices. RMS reflects the effectiveness of the postural control system and MV is related to the amount of regulatory balancing activity associated with the stability level (Hufschmidt et al., 1980; Maki et al., 1990). Given the different aspects of RMS and MV, fallers and non-fallers in this study might have similar levels of postural stability, whereas fallers may require a large amount of regulatory activity from the central nervous system to achieve postural stability.

None of the clinical measures could distinguish fallers from non-fallers. This could be because of the high functional abilities of fallers and non-fallers. For example, although there was a wide range, the cut-off values of timed up and go test to assess fall risk ranged from 10 to 32.6 seconds (Beauchet et al., 2011), and all participants in this study were substantially smaller than the value. High physical function levels were also observed in other clinical measures. It is possible that most clinical measurements are easy, rapid, and useful for assessing frail adults with a high fall risk, but they may be inadequate for detecting potential fall risk in healthy older adults with high physical function. Falls result from a complicated combination of many factors, one of which is postural impairment. Given that postural control is also complex, comprehensive measures using quantitative posturographic measurements, in addition to the

clinical measurements, may be needed to significantly increase the accuracy of fall prediction.

4.3 Study limitations

This study had some limitations. First, we did not obtain details on how the fallers experienced falls. Falls during walking have several causes, including inappropriate weight shifting and tripping (Robinovitch et al., 2013), which are likely related to poor control of the center of mass and swing foot, respectively. The Rm component may predict falls, especially those due to inappropriate weight shifting. Further studies that explore the relationship between Rm components and the detailed information on falls are required to clarify which specific factors the Rm component may predict. Second, this was a cross-sectional study. Longitudinal studies are warranted to explore whether this technique can be used to predict future falls and determine a proper intervention strategy. Finally, the cut-off value is unclear. Further studies are required to generalize our findings to other populations and apply them as a fall-assessment tool in clinical practice.

5. Conclusions

In this study, clinical measurements did not distinguish between older adults with and without a fall history, indicating that older adults with a fall history maintained the same physical functions as those without a fall history. The mean velocity and root mean square of the CoP time series also failed to distinguish differences in fall risk; however, we observed a difference in the rambling component of the CoP trajectories

in the AP direction during quiet standing. If force plate measurements are available, the index based on the rambling-trembling decomposition method, in particular, the mean velocity of the rambling component, could be useful as a sensitive screening biomarker for potential fall risks in healthy adults.

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References

- Alcazar, J., Losa-Reyna, J., Rodriguez-Lopez, C., Alfaro-Acha, A., Rodriguez-Manas, L., Ara, I., Garcia-Garcia, F.J., Alegre, L.M., 2018. The sit-to-stand muscle power test: An easy, inexpensive and portable procedure to assess muscle power in older people. *Exp. Gerontol.* 112, 38-43.
- Ambrose, A.F., Paul, G., Hausdorff, J.M., 2013. Risk factors for falls among older adults: a review of the literature. *Maturitas* 75, 51-61.
- Barker, W., 2014. Assessment and prevention of falls in older people. *Nurs. Older People* 26, 18-24.
- Beauchet, O., Fantino, B., Allali, G., Muir, S.W., Montero-Odasso, M., Annweiler, C., 2011. Timed Up and Go test and risk of falls in older adults: a systematic review. *J. Nutr. Health Aging* 15, 933-938.
- Bohannon, R.W., Bubela, D.J., Magasi, S.R., Wang, Y.C., Gershon, R.C., 2010. Sit-to-stand test: Performance and determinants across the age-span. *Isokinet. Exerc. Sci.* 18, 235-240.
- Costa, E.C., Santinelli, F.B., Moretto, G.F., Figueiredo, C., von Ah Morano, A.E., Barela, J.A., Barbieri, F.A., 2022. A multiple domain postural control assessment in people with Parkinson's disease: traditional, non-linear, and rambling and trembling trajectories analysis. *Gait Posture* 97, 130-136.
- Danna-Dos-Santos, A., Degani, A.M., Zatsiorsky, V.M., Latash, M.L., 2008. Is voluntary control of natural postural sway possible? *J Mot Behav* 40, 179-185.
- Degani, A.M., Leonard, C.T., Danna-Dos-Santos, A., 2017. The effects of early stages of aging on postural sway: A multiple domain balance assessment using a force platform. *J. Biomech.* 64, 8-15.
- Duncan, P.W., Weiner, D.K., Chandler, J., Studenski, S., 1990. Functional reach: a new clinical measure of balance. *J. Gerontol.* 45, M192-197.
- Gerber, E.D., Nichols, P., Giraldo, C., Sidener, L., Huang, C.K., Luchies, C.W., 2022. Rambling-trembling center-of-pressure decomposition reveals distinct sway responses to simulated somatosensory deficit. *Gait Posture* 91, 276-283.
- Hausdorff, J.M., Rios, D.A., Edelberg, H.K., 2001. Gait variability and fall risk in community-living older adults: a 1-year prospective study. *Arch. Phys. Med. Rehabil.* 82, 1050-1056.
- Horak, F.B., 1987. Clinical measurement of postural control in adults. *Phys. Ther.* 67, 1881-1885.
- Hufschmidt, A., Dichgans, J., Mauritz, K.H., Hufschmidt, M., 1980. Some methods and parameters of body sway quantification and their neurological applications. *Arch Psychiatr Nervenkr (1970)* 228, 135-150.
- Kochhann, R., Varela, J.S., Lisboa, C.S.M., Chaves, M.L.F., 2010. The Mini Mental State Examination: Review of cutoff points adjusted for schooling in a large Southern Brazilian sample. *Dement Neuropsychol* 4, 35-41.
- Lindsay, R., James, E.L., Kippen, S., 2004. The Timed Up and Go Test: unable to predict falls on the acute medical ward. *Aust. J. Physiother.* 50, 249-251.
- Maki, B.E., 1997. Gait changes in older adults: predictors of falls or indicators of fear. *J. Am. Geriatr.*

Soc. 45, 313-320.

Maki, B.E., Holliday, P.J., Fernie, G.R., 1990. Aging and postural control. A comparison of spontaneous- and induced-sway balance tests. *J. Am. Geriatr. Soc.* 38, 1-9.

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.

Meekes, W.M., Korevaar, J.C., Leemrijse, C.J., van de Goor, I.A., 2021. Practical and validated tool to assess falls risk in the primary care setting: a systematic review. *BMJ Open* 11, e045431.

Mochizuki, L., Duarte, M., Amadio, A.C., Zatsiorsky, V.M., Latash, M.L., 2006. Changes in postural sway and its fractions in conditions of postural instability. *J. Appl. Biomech.* 22, 51-60.

Prieto, T.E., Myklebust, J.B., Hoffmann, R.G., Lovett, E.G., Myklebust, B.M., 1996. Measures of postural steadiness: differences between healthy young and elderly adults. *IEEE Trans. Biomed. Eng.* 43, 956-966.

Quijoux, F., Vienne-Jumeau, A., Bertin-Hugault, F., Zawieja, P., Lefevre, M., Vidal, P.P., Ricard, D., 2020. Center of pressure displacement characteristics differentiate fall risk in older people: A systematic review with meta-analysis. *Ageing Res Rev* 62, 101117.

Robinovitch, S.N., Feldman, F., Yang, Y., Schonnop, R., Leung, P.M., Sarraf, T., Sims-Gould, J., Loughin, M., 2013. Video capture of the circumstances of falls in elderly people residing in long-term care: an observational study. *Lancet* 381, 47-54.

Rubenstein, L.Z., 2006. Falls in older people: epidemiology, risk factors and strategies for prevention. *Age Ageing* 35 Suppl 2, ii37-ii41.

Sarabon, N., Panjan, A., Latash, M., 2013. The effects of aging on the rambling and trembling components of postural sway: effects of motor and sensory challenges. *Gait Posture* 38, 637-642.

Silva, J., Atalaia, T., Martins, R., Abrantes, J., Aleixo, P., 2022. Centre of pressure kinematics during the Timed Up and Go test in elderly fallers and non-fallers. *Gait Posture* 97, S315-S316.

Swift, C.G., Iliffe, S., 2014. Assessment and prevention of falls in older people--concise guidance. *Clin Med (Lond)* 14, 658-662.

Tinetti, M.E., Kumar, C., 2010. The Patient Who Falls "It's Always a Trade-off". *JAMA* 303.

Tyson, S., Connell, L., 2009. The psychometric properties and clinical utility of measures of walking and mobility in neurological conditions: a systematic review. *Clin. Rehabil.* 23, 1018-1033.

Viccaro, L.J., Perera, S., Studenski, S.A., 2011. Is timed up and go better than gait speed in predicting health, function, and falls in older adults? *J. Am. Geriatr. Soc.* 59, 887-892.

Yamagata, M., Falaki, A., Latash, M.L., 2019a. Effects of Voluntary Agonist-Antagonist Coactivation on Stability of Vertical Posture. *Motor Control* 23, 304-326.

Yamagata, M., Popow, M., Latash, M.L., 2019b. Beyond rambling and trembling: effects of visual feedback on slow postural drift. *Exp. Brain Res.* 237, 865-871.

Yoshinaka, Y., Soga, S., Ota, N., Yokoyama, K., Yamada, Y., Kimura, M., 2018. Light rhythmic exercise with dietary milk fat globule membrane improves physical fitness in an elderly Japanese population: a

380 double-blind randomized placebo-controlled trial. *Biosci. Biotechnol. Biochem.* 82, 677-682.
381 Zatsiorsky, V.M., Duarte, M., 1999. Instant equilibrium point and its migration in standing tasks: rambling
382 and trembling components of the stabilogram. *Motor Control* 3, 28-38.
383 Zatsiorsky, V.M., Duarte, M., 2000. Rambling and trembling in quiet standing. *Motor Control* 4, 185-200.
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Figure legends

Figure 1. Flowchart of research design.

Figure 2. The time profiles of each index in force plate measurements for a representative participant. The top panel represents the ground reaction force in the anteroposterior direction (F_{AP} ; thin black line). Black dots show instantaneous equilibrium points (IEPs), i.e., the instances at which F_{AP} was zero. The middle panel represents the center of pressure in the anteroposterior direction (CoP_{AP} ; thin black line) and rambling (R_m ; thick gray line) trajectories. R_m was the time series computed based on the cubic spline interpolation of the IEP coordinates in the top panel. The bottom panel represents the trembling (Tr ; thick black line) trajectory computed based on the difference between the CoP_{AP} and R_m trajectories in the middle panel.

Figure 3. Box plots of the mean velocity of the center of pressure (CoP_{mv} ; top panel), rambling (R_{mv} ; middle panel), and trembling (Tr_{mv} ; bottom panel) in non-fallers (white box) and fallers (grey box). Left and right panels represent indices in the anteroposterior (AP) and mediolateral (ML) directions. Dots represent the values of each individual. The horizontal lines and red crosses indicate the median and average values of the participants while standing with their eyes open (EO) and closed (EC), respectively. The edges of the boxes represent the 25th and 75th percentiles.

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404 Figure 4. Box plots of the root mean square of the center of pressure (CoP_rms; top panel), rambling
405 (Rm_rms; middle panel), and trembling (Tr_rms; bottom panel) in non-fallers (white box) and fallers (grey
406 box). Left and right panels represent indices in the anteroposterior (AP) and mediolateral (ML) directions.
407 Dots represent the values of each individual. The horizontal lines and red crosses indicate the median and
408 average values of the participants while standing with their eyes open (EO) and closed (EC), respectively.
409 The edges of the boxes represent the 25th and 75th percentiles.