Recurrence Quantification Analysis of Center of Pressure Trajectories for Balance and Fall-Risk Assessment in Young and Older Adults

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***Abstract*—The prevalence and impact of balance impairments and falls in older adults have motivated several studies on the characterization of human balance. This study aimed to determine the ability of recurrence quantification analysis (RQA) measures to characterize balance control during quiet standing in young and older adults and to discriminate between different fall risk groups. We analyze center pressure trajectories in the medial-lateral and anterior-posterior directions from a publicly available static posturography dataset that contains tests acquired under four vision-surface testing conditions. Participants were retrospectively classified as young adults (age<60, n=85), non-fallers (age≥60, falls=0, n=56), and fallers (age≥60, falls≥1, n=18). Mixed ANOVA and post hoc analyzes were performed to test for differences between groups. For CoP fluctuations in the anterior-posterior direction, all RQA measures showed significantly higher values for young than older adults when standing on a compliant surface, indicating less predictable and stable balance control among seniors under testing conditions where sensory information is restricted or altered. However, no significant differences between non-fallers and fallers were observed. These results support the use of RQA to characterize balance control in young and old adults, but not to discriminate between different fall risk groups.**

***Index Terms*—Recurrence quantification analysis, balance control, fall risk, center of pressure, posturography.**

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This work involved human subjects or animals in its research. The authors confirm that all human/animal subject research procedures and protocols are exempt from review board approval.

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I. Introduction

BALANCE control plays a critical role in daily life. Balance is defined as the dynamics of posture control that prevents falls in an individual [1]. Several sensory and motor responses participate in the balance control process to keep the center of mass of the body within the support base [2], [3]. The balance control system is made up of the sensory, central nervous, and motor systems. The sensory system receives information about current and anticipated body status by gathering information from the environment and the body itself (that is, proprioception). This information enables closed-loop and anticipatory balance control mechanisms to generate adequate posture corrections [4], [5], [6]. That is, the central nervous system receives this information and integrates it to determine the best responses of the muscular system to maintain equilibrium. Finally, the information is sent to the specific muscles so that such changes are executed.

Normal aging and some pathological conditions are associated with the deterioration of these systems, which affects balance control. The result of a compromised balance is a higher risk of falling, and it is a prevalent problem in the older adult population. Studies show that about 30% of adults over 65 years of age experience at least one fall per year, with the rate increasing each subsequent year [4], [7]. Falls in older adults can have severe consequences, such as lacerations, dislocations, fractures, trauma, or death. Furthermore, fall-related injuries account for 80% of hospital admissions for the population of this age range [7].

Consequently, several studies have been developed to assess the risk of falling in older adults by analyzing the control mechanisms underlying equilibrium.

Several qualitative and quantitative methods have been used to evaluate balance. One of the most common techniques used is posturography. This technique helps to assess body stability in response to different environmental conditions [8]. During static posturography, the participant must stand still for a fixed period. At this time, the participant is evaluated for their ability to maintain equilibrium. The performance of the participant during the test is helpful to assess overall balance control [9].

Static posturography tests help estimate the center of pressure (CoP) position for its study. The CoP is computed from

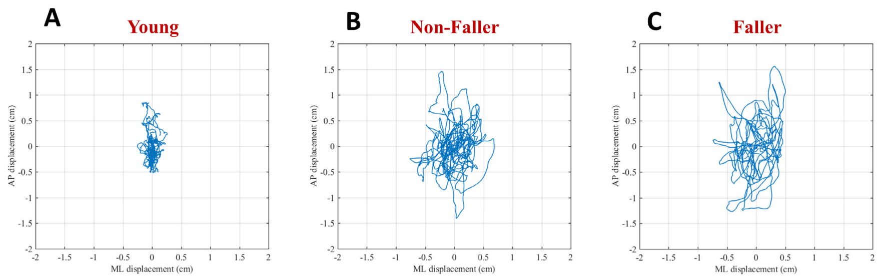

Fig. 1. Center of pressure trajectory for A) a young adult, B) an older adult with no history of falls, and C) an older adult with history of falls. Data sourced from a public dataset [11].

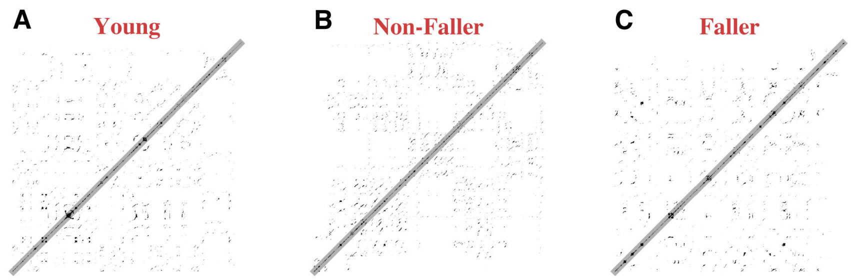

Fig. 2. Recurrence plot for A) a young adult, B) an older adult with no history of falls, and C) an older adult with history of falls. The shaded area represents the Theiler window (1 second). Data sourced from a public dataset [11].

the moment of force and the ground reaction forces of the evaluated participant. Moments and forces are usually acquired using a force plate. CoP is measured in the medial-lateral (ML) and anterior-posterior (AP) directions, corresponding to the right-left and front-back directions, respectively. The plot of both directions against each other allows us to visualize the CoP motion in a 2D plane (Figure 1). Optimal test times range from 60 to 120 seconds [10].

Some studies have proposed the use of non-linear analysis methods to characterize the complex dynamics of physiological signals in general [12], [13]. In particular, several non-linear methods have been used to characterize the structure of CoP trajectories in both the ML and the AP directions. Some of these methods include approximate and sample entropy [14], fractal dimension [15], detrended fluctuation analysis [16], Lyapunov exponents [17], and recurrence quantification analysis (RQA) [18], [19], [20].

This study focuses on RQA, as it presents an advantage over some other nonlinear methods, as most of them require long data series [21]. Furthermore, RQA is robust to transients, outliers, and noise and does not require data stationarity or prerequisites for statistical distribution [22].

RQA is a nonlinear method for data analysis that quantifies the times at which a system returns or recurs to a former state [23]. This method relies on the analysis of recurrence plots (RP) [24]. Recurrence plots represent times when a trajectory revisits the same place in the phase space. The phase space is a mathematical representation of all possible states in a dynamical system [23]. To construct a high-dimensional phase space, Takens introduced the method of time delays in 1981 [25]. This method uses time-delayed copies of the same signal to create a higher-dimensional system. The dimension created is defined by the number of copies used and is called the embedded dimension.

Recurrence plots are a useful tool that allows for the representation of recurrences found in high-dimensional phase spaces in two dimensions (Figure 2). Mathematically, RPs can be defined as follows:

$$R_{i,j}(\varepsilon) = \Theta(\varepsilon - ||\vec{x}_i - \vec{x}_j||), i, j = 1, \ldots, N, \quad (1)$$

where N is the number of measured points, ε is a distance threshold, $||\cdot||$ is a vector norm and Θ is the Heaviside function [23]. The result is a two-dimensional logic matrix, where logic 1 represents the recurrences found in the phase space. Visually, a recurrence plot shows the locations in the phase space where a recurrence occurs.

Qualitative information from a system can be obtained by observing the structures formed by the RPs. However, for a more precise analysis, some measures were proposed by Webber and Zbilut [26] and extended by Marwan et al. [23]. These measures are based on the density of recurrence points and the analysis of the diagonal and vertical structures formed in the RP. Diagonal structures describe the determinism or predictability of a system by measuring the periods in which the system repeats. Vertical structures describe the stability of a system by measuring periods in which the system remains unchanged. References [21] and [27]. Analysis of these measures allows extracting characteristics of the systems studied, such as determinism, entropy, and laminarity [21].

This study aimed to determine the ability of recurrence quantification analysis measures to characterize balance in young and older adults and discriminate between different fall risk groups. The motivation for the study was the development of better balance and fall risk assessment tools for the aging population using a non-linear approach.

II. Materials and Methods

A. Dataset Description

An analysis of CoP trajectories was performed using a public static posturography data set available on PhysioNet (DOI: 10.13026 / C2WW2W) and Figshare (DOI: 10.6084 / m9.

figshare.3394432) [11]. The dataset contains posturography data from 163 participants (116 females and 47 males). The evaluation consisted of recording the participants standing still for 60 seconds under four different conditions: on a rigid surface with eyes open (Open-Rigid), on a rigid surface with closed eyes (Closed-Rigid), on a foam block with eyes open (Open-Foam) and on a foam block with closed eyes (Closed-Foam). Each condition was performed three times, resulting in 12 trials per participant. A total of 1,930 trials were recorded since 26 trials of 5 participants were missing due to their inability to complete the test.

Data acquisition was performed using a force platform at a sampling frequency of 100 Hz. The ground reaction forces and moments were recorded and used to compute the CoP position in the AP and ML axes. The x-axis corresponds to the AP direction, being the x positive anterior and the x negative posterior. The y-axis corresponds to the ML direction, where the y-positive direction is on the right and the y-negative direction is on the left. The authors reported using a 10 Hz fourth-order zero-lag lowpass Butterworth filter on the signals. The potential effects of digital filtering of CoP signals on discrimination between groups have previously been explored. A couple of relevant references are provided for the reader's consideration [28], [29]. Analysis of this data is described in the following subsection.

The data set also contains sociodemographic, anthropometric, and clinical information on participants. In particular, these data include the number of non-intentional falls that participants have experienced during the last 12 months. A non-intentional fall is defined as an event that causes a person to come to rest inadvertently on the ground or any floor or other lower level [30]. Additionally, several qualitative evaluations were performed to assess participants' health status, level of physical activity, cognitive function, and fear of falling.

B. Recurrence Quantification Analysis

Recurrence quantification analysis was performed using the Cross Recurrence Plot Toolbox 5.22 (R32.4) [23]. This toolbox is designed to facilitate the development of recurrence plots (RP), cross-recurrence plots (CRP), and joint recurrence plots (JRP). The toolbox includes several tools and MATLAB routines that allow performing recurrence quantification analysis and extracting measures of the system's recurrences.

The embedded dimension (m) was selected according to previous studies carried out by Hoorn et al. [18], and Negahban et al. [22], in which an optimal embed dimension of 5 was determined using the false nearest neighbor algorithm [31]. Additionally, the time delay was set at 6 based on a previous study by Ramdani et al. [19] with similar CoP data. The threshold of recurrence distance (ε) was established as a fixed percentage of the density of recurrence points in the recurrence plot, also known as the recurrence rate (RR). This approach ensures that neither insufficient nor excessive amounts of recurrences are considered. The advantage of using a fixed percentage instead of a fixed threshold is that it preserves the density of the points without the need to normalize the time series beforehand [23]. In this work, three different values of RR were used (namely, 2%, 3% and 5%). However, only the results for an RR of 5% are presented, as more significant differences between the explored groups were observed using this parameter.

Some additional parameters were considered to avoid potential pitfalls in the analysis [32]. A Theiler window of 1 second was used to exclude temporally close recurrences. In addition, the minimal length of both diagonal and vertical line features was established to 100 ms. This is mainly considered to avoid ceiling effects during analysis [18].

RQA was performed on all available CoP time series, except those of four participants who were excluded due to physical disabilities that affected balance. Thirteen RQA measures were obtained per trial. The average RQA measures were calculated for each participant and condition. This study focused only on measures that describe the diagonal and vertical structures of the recurrence plots (available as supplementary materials). Thus, four measures were selected: two to describe diagonal structures and two to describe vertical structures. The selection was made based on the analysis carried out by Hoorn et al. [18]. The measures that describe diagonal lines are the percentage of determinism (% DET) and the mean length of diagonal lines (L). Measures describing the vertical lines are the percentage of laminarity (% LAM) and the mean length of the vertical line, also known as the trapping time (TT). Table I summarizes these measures and provides guidance for interpretation.

C. Statistical Analysis

Participants were classified into three groups according to their age and history of falls: young, non-fallers, and fallers. Young adults were defined as participants 59 years or younger. Non-fallers were defined as participants 60 years or older without a history of falls in the last 12 months. Fallers were defined as participants aged 60 years or older with one or more falls in the last 12 months. A total of 159 participants were included in this analysis, where 85 were classified as young, 56 as non-fallers, and 18 as fallers. A one-way ANOVA and post hoc analysis was performed to test for differences between these groups in age and basic anthropometric variables. In addition, Fisher's exact test was performed to test for differences in the sex distribution between groups.

Summary statistics (that is, mean and standard deviation) for each RQA measure were calculated for all combinations of group and testing conditions. In addition, box plots were produced to visualize the distribution of the data for all combinations. Summary statistics and visualization were performed using MATLAB R2022a (The Mathworks, Inc., Natick, MA, USA).

Later, mixed-design ANOVA tests were performed to determine the main and interaction effects of two factor variables: group (i.e. Young, Non-Fallers and Fallers) and testing condition (i.e. Open-Rigid, Closed-Rigid, Open-Foam, and Closed-Foam) on each RQA measure. The group and test conditions represent the factors between subjects and within subjects, respectively. The p values were corrected using the Greenhouse-Geisser procedure whenever the compound symmetry assumption was violated (Mauchly's test with

TABLE I
DIAGONAL AND VERTICAL MEASURES SELECTED FROM RECURRENT QUANTIFICATION ANALYSIS AND THEIR MEANING

Diagonal line measures	Vertical line measures
Percentage of Determinism (%DET) Percentage of the trajectory that repeats over time	Percentage of Laminarity (%LAM) Percentage of the trajectory that remains stable over time
Mean diagonal line length (L) Mean length of intervals where the trajectory repeats	Mean vertical line length (TT) Mean length of intervals where the trajectory remained stable

a $p < 0.001$). A corrected p-value<0.05 was accepted as evidence of statistical significance. A significant two-way interaction between the group and the testing condition for a given RQA measure indicated significant differences between at least two combinations of group and condition. Mixed ANOVA tests were performed in R version 4.2.2 using the package rstatix version 0.7.1.

Then, post hoc analyzes were performed to test for differences between groups for each testing condition. These pairwise analyzes were performed using the Mann-Whitney U test (also known as the Wilcoxon rank sum test), a nonparametric test for unpaired samples. A nonparametric test was selected given the nonnormal distribution of the data for some combinations of group and testing conditions (Shapiro-Wilk test with $p < 0.001$). The p-values were corrected for multiple comparisons using the Benjamini-Hochberg method. A p-value < 0.05 was accepted as evidence of statistical significance. Moreover, the magnitude of the difference between the groups was quantified using unbiased Cohen's d. A commonly used interpretation is to refer to this effect size as small ($d = 0.2$), medium ($d = 0.5$), and large ($d = 0.8$) based on the benchmarks suggested by Cohen [33]. Post hoc analyzes were performed in Python version 3 using the library pingouin version 0.5.2.

III. RESULTS

Table II shows the demographic and anthropometric characteristics of the participants by group (i.e., Young, Non-Fallers and Fallers). Significant differences between young and old adults are observed for most continuous variables, except for weight. Interestingly, no significant differences between non-fallers and fallers were found for any continuous variables, which suggests homogeneity in participants' characteristics. In terms of sex distribution by group, a significant difference is observed between the Young and Fallers groups.

Furthermore, tables III and IV show summary statistics by group and condition for the RQA measures in the AP and ML directions, respectively. Moreover, these tables show the results of pairwise comparisons (namely, the p-values and Cohen's d). The results of mixed-design ANOVA and post hoc analysis for each RQA variable are presented in the following subsections.

In addition, figure 3 shows the comparison between groups of the percentage of determinism (%DET), mean diagonal line (L), laminarity (%LAM), and mean vertical line length (TT) by testing conditions. Each sub-figure shows the AP and ML directions. The box plots show the median, upper quartile, and lower quartile. The whiskers represent the maximum value that is not considered an outlier and were calculated using 1.5 times the interquartile range. The circles represent the outlier values, and the notch is depicted as the shaded area in the box plot. Notches that do not overlap between box plots indicate differences between the groups at a 5% significance level. The mean values for each measure are shown as squares and connect each group across testing conditions.

A. Diagonal Lines

1) Percentage of Determinism (%DET): In the ML direction, the mixed ANOVA test with group and testing condition as factors revealed a significant main effect of the testing condition ($F = 8.705$, $p < 0.001$). This effect means that if we ignore the group of participants, some testing conditions lead to significantly different values of determinism. However, this test did not reveal a significant main effect of the group or a significant interaction between factors.

In particular, older adults showed slightly higher mean values of %DET than young adults under the Closed-Foam testing condition. However, no significant differences were found between the groups under different testing conditions.

In the AP direction, the mixed ANOVA test revealed significant main effects of group ($F = 11.469$, $p < 0.001$) and condition ($F = 17.716$, $p < 0.001$). These main effects were qualified by a significant interaction between the group and the testing condition ($F = 2.776$, $p = 0.03$).

In particular, young adults had the highest mean values of %DET, followed by non-fallers. A significant difference was found between young and non-faller adults under all testing conditions. However, a significant difference was only found between young adults and fallers when standing on a foam surface. No significant differences were found between fallers and non-fallers under any testing condition.

2) Mean Diagonal Line Length (L): In the ML direction, the mixed ANOVA test with group and testing condition as factors revealed a significant main effect of the testing condition ($F = 31.938$, $p < 0.001$) and a significant interaction between factors ($F = 5.352$, $p < 0.001$).

In particular, the three groups showed a decrease in mean values of L as the testing condition became more challenging (i.e., more sensory information was altered or restricted). The highest values were observed in the Open-Rigid condition, followed by Closed-Rigid, Open-Foam, and lastly by the Closed-Foam condition. Furthermore, non-fallers showed the lowest mean values among the three groups. However, no significant differences were found between the groups.

In the AP direction, the mixed ANOVA test revealed significant main effects of group ($F = 19.381$, $p < 0.001$) and condition ($F = 67.168$, $p < 0.001$). These main effects were qualified by a significant interaction between the group and the testing condition ($F = 3.091$, $p = 0.013$).

TABLE II
PARTICIPANT CHARACTERISTICS BY GROUP

	One-way ANOVA		Summary statistics by group			Pairwise comparisons		
Variable	F	p value	Young (n = 85) mean (SD)	Non-Fallers (n = 56) mean (SD)	Fallers (n = 18) mean (SD)	Y-F	Y-NF	F-NF
Age, years	722.314	**p <0.001**	27.72 (7.78)	71.54 (6.35)	71.20 (7.12)	**p <0.001**	**p <0.001**	0.984
Height, cm	26.212	**p <0.001**	166.81 (8.75)	157.77 (8.73)	155.19 (6.16)	**p <0.001**	**p <0.001**	0.502
Weight, kg	2.239	0.11	61.62 (7.73)	63.96 (8.43)	60.01 (8.1)	0.718	0.207	0.163
BMI, kg/m^2	26.647	**p <0.001**	22.20 (2.82)	25.71 (2.97)	24.88 (2.84)	**p <0.001**	**p <0.001**	0.540
			Fisher's Exact Test					
Variable			Young (n = 85) male / female	Non-Fallers (n = 56) male / female	Fallers (n = 18) male / female	Y-F	Y-NF	F-NF
Sex			30 / 55	13 / 43	1 / 17	**p <0.05**	0.139	0.165

In particular, young adults had the highest mean L values. On the Open-Rigid condition, a significant difference was found only between young adults and non-fallers, while in the rest of the conditions (Closed-Rigid, Open-Firm, Closed-Foam), significant differences were observed between young and both groups of older adults. No significant differences were found between fallers and non-fallers under any testing condition.

B. Vertical Lines

1) Percentage of Laminarity (%LAM): In the ML direction, the mixed ANOVA test with group and testing condition as factors revealed a significant main effect of the testing condition ($F = 3.979$, $p = 0.021$) and a significant interaction between factors ($F = 3.99$, $p = 0.004$).

In particular, fallers showed slightly higher mean values of %LAM than the rest of the groups under three testing conditions. Slightly lower values were observed under closed-eye testing conditions. However, no significant differences were found between the groups under any condition.

In the AP direction, the mixed ANOVA test revealed significant main effects of group ($F = 17.087$, $p < 0.001$) and condition ($F = 35.665$, $p < 0.001$). These main effects were qualified by a significant interaction between the group and the testing condition ($F = 2.582$, $p = 0.036$).

In particular, young adults had the highest mean values of %LAM, followed by non-fallers. The results also showed that the highest values were observed in the Open-Rigid condition, followed by the Closed-Rigid, Open-Foam, and Closed-Foam, with the latter producing the lowest values. Under the Open-Rigid condition, a significant difference was found between young and non-faller adults only, while in the rest of the conditions (Closed-Rigid, Open-Foam, Closed-Foam), a significant difference was found between young and both groups of older adults. No significant differences were found between faller and non-faller adults under any testing condition.

2) Trapping Time (TT): In the ML direction, the mixed ANOVA test with group and testing condition as factors revealed a significant main effect of the testing condition ($F = 27.996$, $p < 0.001$) and a significant interaction between factors ($F = 8.838$, $p < 0.001$).

In particular, results from tests when standing on a rigid surface were the only that showed significant differences between young adults and non-fallers. Under these conditions, young adults showed the highest mean TT values followed by non-fallers. In contrast, under foam surface conditions, the fallers showed the highest values and the young adults the lowest. However, no significant differences were found between the groups. In general, the results between the conditions showed that the highest values were observed in the Open-Rigid condition, followed by Closed-Rigid, Open-Foam, and Closed-Foam with the lowest values.

In the AP direction, the mixed ANOVA test revealed significant main effects of group ($F = 25.38$, $p < 0.001$) and condition ($F = 40.695$, $p < 0.001$). These main effects were qualified by a significant interaction between the group and the testing condition ($F = 2.787$, $p = 0.021$).

In particular, young adults had higher mean TT values than older adults. Significant differences were observed between young and older adults under all testing conditions, but no significant differences were observed between fallers and non-fallers. The results also showed that the highest values were observed in the Open-Rigid condition, followed by Closed-Rigid, Open-Foam, and Closed-Foam with the lowest values.

In particular, the Open-Foam condition in the AP direction showed the most consistent results for the four measures. Young adults showed the highest values, followed by non-fallers and fallers. Furthermore, significant differences ($p < 0.001$) were observed between young and older adults for the four measures.

IV. DISCUSSION

A. Main Findings

Young adults showed generally higher values in all RQA measures than older adults when considering only statistically significant differences, indicating more predictable and stable CoP fluctuations. More specifically, young adults exhibited statistically significant higher values than non-fallers for all measures in the AP direction. However, the differences between young adults and fallers were statistically significant mainly for L, % LAM, and TT. In contrast, in the ML direction, only TT under the Open-Firm and Closed-Firm testing conditions showed statistically significant differences

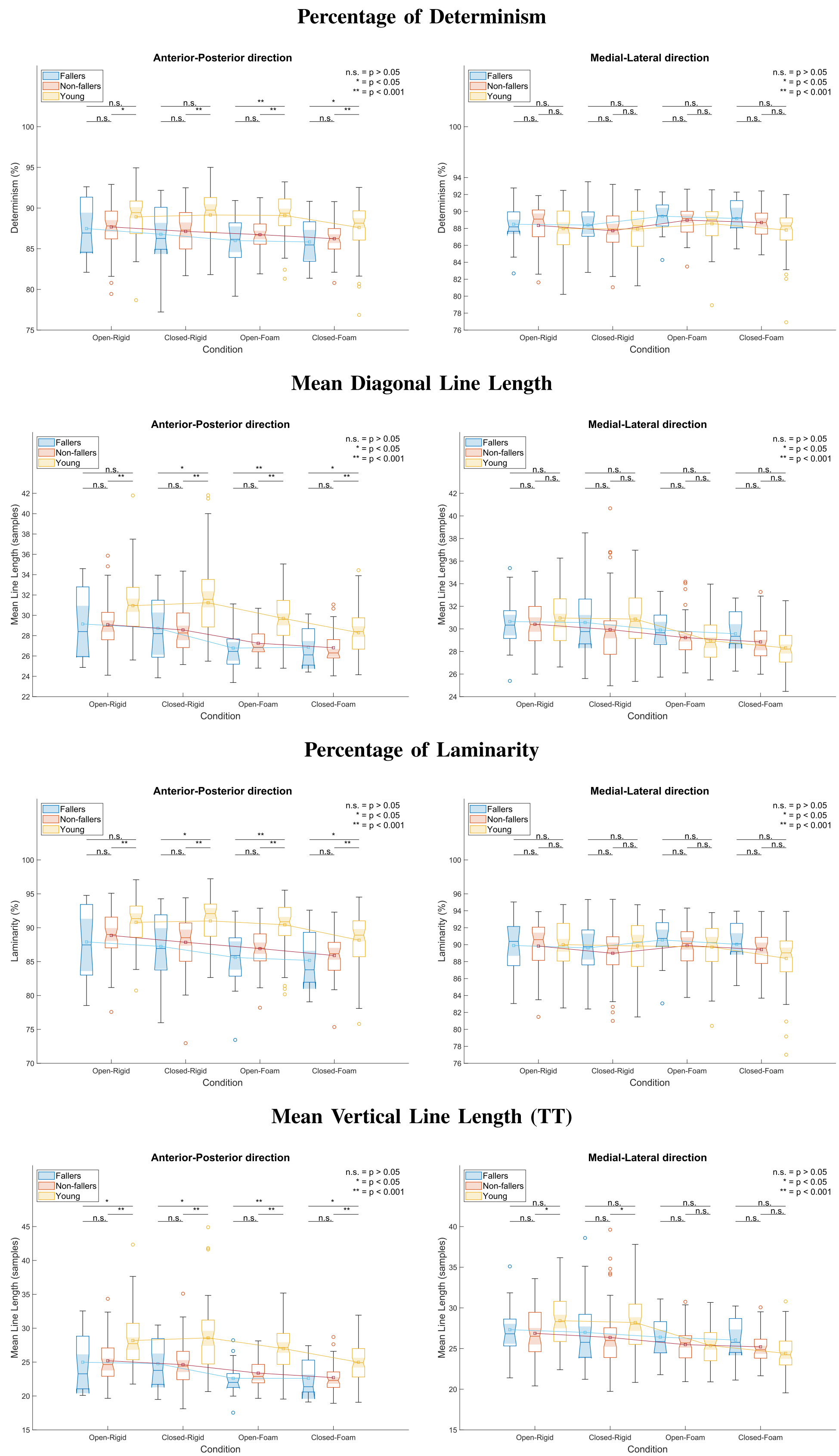

Fig. 3. Measures by group and testing condition. The box plots show the median, upper quartile, and lower quartile. Whiskers show 1.5 times the interquartile range from the upper and lower quartiles and the circles depict the outlier values. Mean values (depicted as squares) were plotted to facilitate the comparison between groups across testing conditions.

TABLE III
SUMMARY STATISTICS BY GROUP AND CONDITION AND PAIRWISE COMPARISONS BETWEEN GROUPS FOR RQA MEASURES IN THE AP DIRECTION

Summary statistics				Corrected p-value			Cohen's d		
Variable	Young (Y) mean (SD)	Non-Fallers (NF) mean (SD)	Fallers (F) mean (SD)	NF-Y	F-Y	F-NF	NF-Y	F-Y	F-NF
Eyes Open - Rigid Surface									
%DET	0.89 (0.03)	0.88 (0.03)	0.87 (0.04)	**0.02**	0.41	0.94	-0.459	-0.439	0.004
L	30.95 (2.89)	29.08 (2.37)	29.15 (3.36)	**p <0.001**	0.13	1	-0.705	-0.562	0.086
%LAM	0.91 (0.03)	0.89 (0.04)	0.88 (0.05)	**p <0.001**	0.21	0.89	-0.6	-0.768	-0.179
TT	28.18 (3.96)	25.2 (3.11)	24.99 (4.34)	**p <0.001**	**0.01**	0.67	-0.828	-0.759	-0.012
Closed Eyes - Rigid Surface									
%DET	0.89 (0.03)	0.87 (0.03)	0.87 (0.04)	**p <0.001**	0.07	0.94	-0.729	-0.739	-0.067
L	31.24 (3.29)	28.56 (2.2)	28.72 (3.21)	**p <0.001**	**0.02**	0.92	-0.931	-0.746	0.104
%LAM	0.91 (0.03)	0.88 (0.04)	0.87 (0.05)	**p <0.001**	**0.01**	1	-0.894	-0.979	-0.104
TT	28.58 (4.53)	24.62 (3.1)	24.77 (3.99)	**p <0.001**	**0.01**	0.96	-0.993	-0.833	0.084
Eyes Open - Foam Surface									
%DET	0.89 (0.03)	0.87 (0.02)	0.86 (0.03)	**p <0.001**	**p <0.001**	0.67	-0.998	-1.114	-0.252
L	29.7 (2.46)	27.25 (1.38)	26.78 (2.05)	**p <0.001**	**p <0.001**	0.32	-1.159	-1.161	-0.221
%LAM	0.9 (0.03)	0.87 (0.03)	0.86 (0.05)	**p <0.001**	**p <0.001**	0.47	-1.088	-1.25	-0.304
TT	26.99 (3.44)	23.37 (1.93)	22.61 (2.63)	**p <0.001**	**p <0.001**	0.32	-1.231	-1.28	-0.3
Closed Eyes - Foam Surface									
%DET	0.88 (0.03)	0.86 (0.02)	0.86 (0.03)	**p <0.001**	**0.04**	0.76	-0.535	-0.619	-0.178
L	28.3 (2.15)	26.81 (1.45)	26.86 (1.92)	**p <0.001**	**0.02**	0.76	-0.781	-0.679	0
%LAM	0.88 (0.04)	0.86 (0.03)	0.85 (0.04)	**p <0.001**	**0.02**	0.74	-0.638	-0.76	-0.21
TT	24.98 (2.91)	22.71 (1.98)	22.61 (2.62)	**p <0.001**	**0.01**	0.65	-0.875	-0.828	-0.051

TABLE IV
SUMMARY STATISTICS BY GROUP AND CONDITION AND PAIRWISE COMPARISONS BETWEEN GROUPS FOR RQA MEASURES IN THE ML DIRECTION

Summary statistics				Corrected p-value			Cohen's d		
Variable	Young (Y) mean (SD)	Non-Fallers (NF) mean (SD)	Fallers (F) mean (SD)	NF-Y	F-Y	F-NF	NF-Y	F-Y	F-NF
Eyes Open - Rigid Surface									
%DET	0.88 (0.03)	0.88 (0.02)	0.88 (0.02)	0.52	0.52	1	0.129	0.21	0.089
L	30.96 (2.39)	30.41 (2.32)	30.65 (2.54)	0.37	0.77	0.68	-0.263	-0.107	0.151
%LAM	0.9 (0.03)	0.9 (0.03)	0.9 (0.03)	1	1	1	-0.074	-0.048	0.025
TT	28.43 (3.13)	26.87 (3.17)	27.32 (3.37)	**0.04**	0.34	0.66	-0.519	-0.331	0.179
Closed Eyes - Rigid Surface									
%DET	0.88 (0.03)	0.88 (0.03)	0.88 (0.03)	0.52	0.86	0.52	-0.099	0.143	0.24
L	30.87 (2.6)	29.94 (2.98)	30.56 (3.26)	0.09	0.48	0.64	-0.384	-0.156	0.206
%LAM	0.9 (0.03)	0.89 (0.03)	0.9 (0.03)	0.34	0.92	1	-0.304	-0.131	0.164
TT	28.2 (3.47)	26.36 (3.91)	26.98 (4.44)	**0.01**	0.15	0.9	-0.549	-0.367	0.159
Eyes Open - Foam Surface									
%DET	0.89 (0.02)	0.89 (0.02)	0.89 (0.02)	0.52	0.28	0.52	0.205	0.45	0.297
L	28.96 (1.78)	29.23 (1.78)	29.9 (1.96)	0.56	0.19	0.26	0.149	0.556	0.407
%LAM	0.9 (0.03)	0.9 (0.02)	0.91 (0.03)	1	0.5	0.5	0.066	0.338	0.303
TT	25.36 (2.28)	25.48 (2.34)	26.41 (2.53)	0.9	0.21	0.33	0.052	0.485	0.422
Closed Eyes - Foam Surface									
%DET	0.88 (0.02)	0.89 (0.02)	0.89 (0.02)	0.28	0.28	0.52	0.408	0.574	0.271
L	28.31 (1.73)	28.85 (1.54)	29.57 (2.01)	0.22	0.09	0.26	0.321	0.704	0
%LAM	0.88 (0.03)	0.89 (0.02)	0.9 (0.03)	0.34	0.34	0.51	0.381	0.554	0.278
TT	24.41 (2.21)	25.21 (1.94)	26.05 (2.73)	0.09	0.08	0.25	0.382	0.715	0.391

between young adults and non-fallers. This suggests that quantifying recurrences in CoP fluctuations in the ML direction is not particularly discriminative between these groups. Further analyzes are suggested to determine whether these results show underlying differences or were found by chance (that is, type I error). Therefore, results in the ML direction will not be discussed further in this paper.

This difference between the AP and ML directions could be explained by the strategies used for balance control during standing described by Winter [1]. During quiet standing and small perturbations, the ankle strategy, which relies on the ankle's plantar flexor / dorsiflexor muscles alone, is sufficient to control balance. This strategy is responsible for the fluctuations in AP CoP. In more perturbed situations or when the ankle muscles cannot act (e.g., ankle motion is restricted), a hip strategy would respond to flex or extend the hip to move the body's center of mass posteriorly or anteriorly, respectively. This strategy is responsible for ML CoP fluctuations. The above results suggest that standing on firm and flexible surfaces (e.g., foam) activates these two strategies differently. Generally speaking, a decreasing trend in mean values for all RQA measures in the AP direction can be observed across testing conditions, from Open-Rigid to Closed-Rigid to Open-Foam to Closed-Foam. In other words, the more challenging the testing condition, the less deterministic and stable the CoP motion is in the AP direction. In contrast, the CoP motion becomes less deterministic in the ML direction when participants are deprived of visual information but increases again when their plantar sensation is altered. This change in determinism is reflected as a decreasing line from Open-Rigid to Closed-Rigid and an increasing line from Closed-Rigid to Open-Foam (i.e. when changing the standing surface).

The diagonal line measures characterize the determinism of the system by quantifying the number of intervals where the trajectory repeats [percentage of determinism (%DET)] and their duration [mean diagonal length (L)]. A higher determinism (that is, a higher %DET) indicates a more predictable and less random CoP trajectory. Furthermore, longer recurrences (i.e. higher L values) indicate more similar temporal dynamic CoP patterns. In other words, higher values of % DET and L result from CoP fluctuations whose trajectory tends to repeat over time. Therefore, higher values of % DET and L during quiet standing are more likely to reflect appropriate balance control in the presence of perturbations (e.g., standing on a compliant surface). On the contrary, lower values % DET and L arise from CoP trajectories that change direction over time due to perturbations, showing a less optimal balance control [18]. This interpretation is consistent with our results, as young adults, expected to have a better balance control, showed the highest values for %DET and L than the other two groups.

The vertical line measures indicate the stability of the trajectory by quantifying the time that the CoP remained in nearly the same position. The mean vertical line length (TT) is related to long periods of stability in the CoP trajectory. Higher TT values indicate longer periods of minimal postural sway. This might reflect a balance between the torques produced by gravity and postural muscles, resulting in a more accurate balance control. Hence, younger adults are more likely to be better able to control muscle torque and match it to the required torque due to gravity. This interpretation is consistent with our results, as young adults had the highest TT values. Furthermore, the overall stability of the CoP trajectories appeared to be strongly affected, as TT showed a significant difference with the lowest p-values between young and older adults in all testing conditions (p-value ≤ 0.01). This can be interpreted as an increase in postural sway in older adults compared to young adults regardless of the condition, relating to a decrease in balance control [3].

Similarly, the percentage of laminarity (%LAM) relates to the proportion of time the trajectory remained stable throughout the test. The highest values for laminarity were found in the young group, followed by the non-fallers and fallers with the lowest values. The %LAM is directly related to the amount of time a CoP trajectory remained stable. These results show that fallers tend to have more movement in their CoP over time than the two other groups showing an overall less stable CoP trajectory.

The interpretation of the RQA measures described above considers that a more deterministic structure of CoP fluctuations speaks of a more regular and stable balance control. This interpretation is shared by other authors, whose results are consistent with those of the present study [18], [34], [35], [36], [37]. This interpretation is further supported by the results of a previous study using approximate entropy and sample entropy to quantify the regularity of CoP fluctuations [14]. In this study, young adults exhibited significantly higher regularity (i.e. lower entropy values) than older adults, which is related to determinism. Moreover, non-fallers showed slightly higher regularity than fallers, which is in line with the results from the present study.

An alternative interpretation considers that more deterministic CoP fluctuations reflect less complexity, and thus less behavioral flexibility. This interpretation was proposed based on studies on multiple sclerosis, a history of falls, and knee osteoarthritis patients [19], [20], [22]. However, it must be noted that random noise exhibits low determinism yet does not have a complex structure. Thus, complexity cannot be directly deduced from low determinism. Furthermore, their divergent results could derive from balance control mechanisms specific to some problems (e.g., multiple sclerosis and knee osteoarthritis). This difference might also arise from different RQA settings. For example, Ramdani et al. did not report the use of a Theiler window [19], which strongly influences the results, thus overestimating diagonal line measures by including temporally close recurrences [32].

Balance control is also affected when the sources of sensory information required to maintain balance are altered or restricted. In general, the central nervous system integrates information from visual, vestibular, cutaneous, and proprioceptive stimuli during balance control [3], [38]. Depriving an individual of these information sources allows to assess its contribution to balance control. Young adults did not show noticeable changes in balance control when skin sensation or visual information was restricted during the tests. Only a slight balance decrease was observed when both conditions were restrained simultaneously, as the studied measures indicated a more random and less stable CoP movement under this condition. This may be because vestibular and proprioceptive information alone was not sufficient to maintain the same accuracy in balance control. However, the changes were minimal and the overall balance control was not significantly affected.

In contrast, older adults showed the worst balance control when sensory information is altered or restricted due to impaired balance control due to aging [39]. The foam surface showed a more significant impact on balance control than vision. This may be partially explained, as the characteristics of the foam surface can affect movement by cushioning ankle movement in addition to removing skin information [40]. However, the results showed that the foam surface barely affected the balance in young adults, affecting the balance of falling adults. This indicates that as sensory mechanisms decline, the faller population relies more on information gathered from skin receptors to maintain balance during quiet standing.

Therefore, the best condition to study the differences between the groups was that the eyes were open with a foam surface, which is consistent with the results presented as this was the only condition that showed significant differences ($p < 0.001$) between young and both groups of older adults for all measures studied. As stated previously, it was observed that the deprivation of this condition was insufficient to affect balance in young adults while significantly affecting older adults.

In summary, for all AP measures, young adults showed significantly higher values than older adults. Standing with eyes open on a foam surface seems to be the best testing condition to assess balance control when looking for differences between groups, as significant differences were observed for all measures between young and older adults and the effect size of those differences was large (0.998-1.28).

B. Limitations and Future Work

The main limitation of this study was the use of a data set with a relatively small number of participants in the fallers group ($n = 18$), which hinders statistical power. A larger dataset would increase statistical power, which would allow slight differences to be detected as significant differences.

Furthermore, a different approach to classifying study groups could result in a better study of balance control dynamics by group. For example, some evidence considers that fallers who have suffered a fall are more closely related to non-fallers than to fallers [41]. This results from the supposition that the cause of one-in-a-lifetime falls does not necessarily indicate impaired balance control. Some evidence supporting this statement shows that older adults with one fall only showed postural dynamics and muscle strength similar to those of non-fallers [4]. Therefore, further studies may classify older adults as multi-fallers and nonmultiple-fallers. The first group would include older adults with one or fewer falls and the latter older adults with two or more falls. Another method of reclassification proposes the inclusion of age in the category of old adults (60 in this study). Although in the present study, this was not considered a determining factor. As the sociodemographic analysis showed in table II, both fallers and non-fallers showed a mean age of 71 with no significant differences between them. However, consideration of this parameter could be evaluated differently depending on the data studied.

Another limitation is the retrospective approach to the study of falls used to determine the risk of falls. This approach is not optimal to identify a decline in balance control mechanisms, as impaired balance may be present when old adults have not yet suffered from falls. Better approaches include prospective studies, in which participants are monitored after the posturography test. This analysis would allow for a more accurate selection of adults at risk of falls. The results of this type of study recorded a higher incidence of falls in the adults studied [4]. However, prospective analysis is more difficult to achieve as it would involve follow-up studies to classify the groups. In this case, the limitation was subject to the publicly available dataset.

RQA must be performed with some additional considerations. The most crucial factor to consider is selecting the input parameters that significantly affect the analysis results. In this study, different distance thresholds were considered to optimize system recurrences, as lower threshold values reduce the number of recurrences found in the system. Further studies explore adjusting other parameters to determine their optimal values. Although this would be an interesting topic, the determination of optimal parameters is beyond the scope of this study. However, the reader is referred to another study on the effect of recurrence rate on RQA measures reliability [42].

Furthermore, considering additional RQA measures in addition to those described in this study could provide a more complete description of CoP and therefore better insight into postural control mechanisms. This can also complement other types of CoP analysis, as some of the measures relate to other nonlinear methods (e.g., Shannon entropy and Lyapunov exponents).

Finally, other approaches include considering other postural evaluations, as they may provide better solutions for preventing falls in older adults. Some of these approaches explore other causes for falling in addition to balance control decline. These include qualitative evaluations related to psychological factors and fear of falling [43].

V. Conclusion

This study explored recurrence quantification analysis as a tool to characterize the nonlinear dynamics of balance control during quiet standing in young and older adults and its ability to discriminate between fall risk groups. The results suggest that the anterior-posterior CoP fluctuations are more helpful in identifying differences between groups than the medial-lateral fluctuations, as the latter produced only a couple of significant differences in the RQA measures. Furthermore, CoP trajectories in young adults were more recurrent than in older adults. Fallers presented the lowest stability values in their trajectories.

The measures studied were also affected by altered sensory information under each condition. Young adults showed low variability in their CoP movement under normal conditions and when a source of sensory information is altered or restricted (closed eyes or foam surface). However, a more random and less stable movement was observed when both sensory information sources were altered or restricted. A similar trend was identified in the faller adults standing on a foam surface, showing a more considerable decline in balance control than in the other groups. This suggests that information received from cutaneous receptors is more relevant for maintaining balance control in the faller population due to the decline of other sources of balance information. Moreover, TT seemed to be the most sensitive measure for assessing differences in balance control mechanisms between groups, although no significant differences were found between fallers and non-fallers. This is mainly attributed to the low sample of faller participants, which reduced the power of the statistical analyses.

In general, a trend for more deterministic and stable balance control was found in young adults than in older adults according to recurrence analysis. Testing conditions seemed to be a determinant in the assessment of the balance. The foam surface with eyes open appeared to be the most sensitive measure to assess balance control differences between groups. However, more studies are required to produce additional supporting evidence.

References

[1] D. A. Winter, "Human balance and posture control during standing and walking," *Gait Posture*, vol. 3, no. 4, pp. 193–214, 1995.

[2] F. B. Horak, "Postural orientation and equilibrium: What do we need to know about neural control of balance to prevent falls?" *Age Ageing*, vol. 35, no. 2, pp. 7–11, Sep. 2006.

[3] J. H. Van Dieën and M. Pijnappels, "Balance control in older adults," in *Locomotion and Posture in Older Adults*. Cham, Switzerland: Springer, pp. 237–262, 2017.

[4] S. R. Lord, C. Sherrington, and H. B. Menz, *Falls in Older People: Risk Factors and Strategies for Prevention*. Cambridge, U.K.: Cambridge Univ. Press, 1999.

[5] I. D. Loram, C. N. Maganaris, and M. Lakie, "Paradoxical muscle movement in human standing," *J. Physiol.*, vol. 556, no. 3, pp. 683–689, May 2004.

[6] M. L. Latash, "Exemplary behaviors," in *Fundamentals of Motor Control*. Amsterdam, The Netherlands: Elsevier, 2012, pp. 211–259.

[7] P. Kannus, H. Sievänen, M. Palvanen, T. Järvinen, and J. Parkkari, "Prevention of falls and consequent injuries in elderly people," *Lancet*, vol. 366, no. 9500, pp. 1885–1893, Dec. 2005.

[8] C. Porto, T. Lemos, and A. S. Ferreira, "Analysis of the postural stabilization in the upright stance using optimization properties," *Biomed. Signal Process. Control*, vol. 52, pp. 171–178, Jul. 2019.

[9] J. H. Pasma, D. Engelhart, A. C. Schouten, H. van der Kooij, A. B. Maier, and C. G. M. Meskers, "Impaired standing balance: The clinical need for closing the loop," *Neuroscience*, vol. 267, pp. 157–165, May 2014.

[10] R. Pilkar, N. Arzouni, and K. J. Nolan, "Postural stability during long duration quiet standing in post stroke hemiplegia," *Biomed. Signal Process. Control*, vol. 39, pp. 162–168, Jan. 2018.

[11] D. A. Santos and M. Duarte, "A public data set of human balance evaluations," *PeerJ*, vol. 4, p. e2648, Nov. 2016.

[12] L. Glass and D. Kaplan, "Time series analysis of complex dynamics in physiology and medicine," *Med. Prog. Through Technol.*, vol. 19, pp. 28–115, Feb. 1993.

[13] O. Faust and M. G. Bairy, "Nonlinear analysis of physiological signals: A review," *J. Mech. Med. Biol.*, vol. 12, no. 4, pp. 1–22, 2012.

[14] L. Montesinos, R. Castaldo, and L. Pecchia, "On the use of approximate entropy and sample entropy with centre of pressure time-series," *J. NeuroEngineering Rehabil.*, vol. 15, no. 1, pp. 1–15, Dec. 2018.

[15] N. Kuznetsov, S. Bonnette, J. Gao, and M. A. Riley, "Adaptive fractal analysis reveals limits to fractal scaling in center of pressure trajectories," *Ann. Biomed. Eng.*, vol. 41, no. 8, pp. 1646–1660, Aug. 2013.

[16] V. von Tscharner, P. Zandiyeh, and P. Federolf, "Is sample entropy based entropic half-life and de-trended fluctuation analysis correlated and do they reflect phase regularity of center of pressure measurements?" *Biomed. Signal Process. Control*, vol. 24, pp. 103–108, Feb. 2016.

[17] T. Siragy and J. Nantel, "Quantifying dynamic balance in young, elderly and Parkinson's individuals: A systematic review," *Frontiers Aging Neurosci.*, vol. 10, pp. 1–22, Nov. 2018.

[18] W. van den Hoorn, G. K. Kerr, J. H. van Dieën, and P. W. Hodges, "Center of pressure motion after calf vibration is more random in fallers than non-fallers: Prospective study of older individuals," *Frontiers Physiol.*, vol. 9, pp. 1–17, Mar. 2018, Art. no. 273.

[19] S. Ramdani, G. Tallon, P. L. Bernard, and H. Blain, "Recurrence quantification analysis of human postural fluctuations in older fallers and non-fallers," *Ann. Biomed. Eng.*, vol. 41, no. 8, pp. 1713–1725, Aug. 2013.

[20] H. Negahban, M. A. Sanjari, M. Karimi, and M. Parnianpour, "Complexity and variability of the center of pressure time series during quiet standing in patients with knee osteoarthritis," *Clin. Biomechanics*, vol. 32, pp. 280–285, Feb. 2016.

[21] N. Marwan, N. Wessel, U. Meyerfeldt, A. Schirdewan, and J. Kurths, "Recurrence-plot-based measures of complexity and their application to heart-rate-variability data," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 66, no. 2, pp. 1–8, Aug. 2002.

[22] H. Negahban, M. A. Sanjari, R. Mofateh, and M. Parnianpour, "Nonlinear dynamical structure of sway path during standing in patients with multiple sclerosis and in healthy controls is affected by changes in sensory input and cognitive load," *Neurosci. Lett.*, vol. 553, pp. 126–131, Oct. 2013.

[23] N. Marwan, M. C. Romano, M. Thiel, and J. Kurths, "Recurrence plots for the analysis of complex systems," *Phys. Rep.*, vol. 438, nos. 5–7, pp. 237–329, 2007.

[24] J.-P. Eckmann, S. O. Kamphorst, and D. Ruelle, "Recurrence plots of dynamical systems," *Europhys. Lett.*, vol. 4, no. 9, pp. 973–977, Nov. 1987.

[25] F. Takens, "Detecting strange attractors in turbulence," in *Dynamical Systems and Turbulence, Warwick 1980*. Heidelberg, Germany: Springer, 1981, pp. 366–381.

[26] C. L. Webber and J. P. Zbilut, "Dynamical assessment of physiological systems and states using recurrence plot strategies," *J. Appl. Physiol.*, vol. 76, no. 2, pp. 965–973, Feb. 1994.

[27] C. Webber and J. Zbilut, "Recurrence quantification analysis of nonlinear dynamical systems," *Tutorials Contemp. Nonlinear Methods Behav. Sci.*, vol. 94, pp. 26–94, Jan. 2005.

[28] C. K. Rhea, A. W. Kiefer, W. G. Wright, L. D. Raisbeck, and F. J. Haran, "Interpretation of postural control may change due to data processing techniques," *Gait Posture*, vol. 41, no. 2, pp. 731–735, Feb. 2015.

[29] L. H. F. Giovanini, S. M. Silva, E. F. Manffra, and J. C. Nievola, "Sampling and digital filtering effects when recognizing postural control with statistical tools and the decision tree classifier," *Proc. Comput. Sci.*, vol. 108, pp. 129–138, 2017.

[30] *Falls*, World Health Organization, Geneva, Switzerland, Apr. 2021.

[31] M. B. Kennel, R. Brown, and H. D. I. Abarbanel, "Determining embedding dimension for phase-space reconstruction using a geometrical construction," *Phys. Rev. A, Gen. Phys.*, vol. 45, no. 6, p. 3403, Mar. 1992.

[32] N. Marwan, "How to avoid potential pitfalls in recurrence plot based data analysis," *Int. J. Bifurcation Chaos*, vol. 21, no. 4, pp. 1003–1017, 2011.

[33] D. Lakens, "Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for t-tests and ANOVAs," *Frontiers Psychol.*, vol. 4, p. 863, Nov. 2013.

[34] M. A. Riley, R. Balasubramaniam, and M. T. Turvey, "Recurrence quantification analysis of postural fluctuations," *Gait Posture*, vol. 9, no. 1, pp. 65–78, Mar. 1999.

[35] M. A. Riley and S. Clark, "Recurrence analysis of human postural sway during the sensory organization test," *Neurosci. Lett.*, vol. 342, nos. 1–2, pp. 45–48, May 2003.

[36] J. M. Haddad, R. E. A. Van Emmerik, J. S. Wheat, and J. Hamill, "Developmental changes in the dynamical structure of postural sway during a precision fitting task," *Exp. Brain Res.*, vol. 190, no. 4, pp. 431–441, Oct. 2008.

[37] M. Mazaheri, M. Salavati, H. Negahban, M. A. Sanjari, and M. Parnianpour, "Postural sway in low back pain: Effects of dual tasks," *Gait Posture*, vol. 31, no. 1, pp. 116–121, Jan. 2010.

[38] J. Maitre and T. P. Paillard, "Influence of the plantar cutaneous information in postural regulation depending on the age and the physical activity status," *Frontiers Human Neurosci.*, vol. 10, p. 409, Aug. 2016.

[39] N. L. Choy, S. Brauer, and J. Nitz, "Changes in postural stability in women aged 20 to 80 years," *Journals Gerontology A, Biol. Sci. Med. Sci.*, vol. 58, no. 6, pp. M525–M530, Jun. 2003.

[40] M. Patel et al., "The effects of foam surface properties on standing body movement," *Acta Oto-Laryngologica*, vol. 128, no. 9, pp. 952–960, 2008.

[41] T. Masud and R. O. Morris, "Epidemiology of falls," *Age Ageing*, vol. 30, no. S4, pp. 3–7, Nov. 2001.

[42] W. van den Hoorn, P. W. Hodges, J. H. van Dieën, and G. K. Kerr, "Reliability of recurrence quantification analysis of postural sway data. A comparison of two methods to determine recurrence thresholds," *J. Biomechanics*, vol. 107, Jun. 2020, Art. no. 109793.

[43] L. Thiamwong and J. Suwanno, "Fear of falling and related factors in a community-based study of people 60 years and older in Thailand," *Int. J. Gerontology*, vol. 11, no. 2, pp. 80–84, Jun. 2017.