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Using nonlinear measures to evaluate postural control in healthy adults during bipedal standing on an unstable surface

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Purpose: This study examined the use of nonlinear measures – sample entropy (SampEn), fractal dimension (FD), and the Lyapunov exponent (LyE) – to evaluate postural control in adults during standing on an unstable surface, with and without visual feedback. *Methods*: 14 healthy young adults (24.07 ± 7.32 years) completed bipedal standing trials on an unstable-plate Biodex Balance System (BBS) connected to a Vicon system, with eyes open and closed. Each trial lasted 20 sec. Analysis was performed based on the center of mass (CoM), for which the three nonlinear measures were calculated. *Results*: Excluding visual feedback was found to cause a significant increase in linear and nonlinear parameters. Moreover, SampEn and FD values were found to be significantly higher in the PD direction, compared to AP or ML, whereas LyE values in this direction were minimal. *Conclusions*: Results show that the three nonlinear measures provide a useful way of evaluating postural control in healthy adults. Moreover, it seems that introducing an unstable surface meant that the projection of the CoM was not perpendicular to the surface, but rather set at a certain continually changing angle, forcing the whole system to adapt to chaotic and unpredictable conditions. Such refined changes in conditions can be evaluated in a precise way only by using nonlinear measures.

Key words: fractal dimension, sample entropy, Lyapunov exponent, visual control, center of mass

1. Introduction

Postural control while maintaining an upright standing posture is a fundamental motor skill that provides the basis for most movement tasks. The postural control system regulates the body's sway during upright standing through the complex interaction of somatosensory, visual and vestibular sensory feedback networks, numerous brain regions, and the musculoskeletal system [16]. A number of papers [3], [22], [29] have recently been trying to assess this complexity of postural control more directly. In these approaches, complexity is assumed to be directly related to the properties of stability and adaptability that characterize healthy and efficient systems. It is also closely linked to the degree of organization, or coordination, between the multiple components that compose the system. When components are independent, the system is unable to exhibit any kind of coordinated activity, and its behavior remains erratic and unpredictable, whereas when organization is too strict, or coordination too rigid, the system tends to behave in a very predictable and deterministic way. Complexity, in the present context, can be defined as a compromise between order and disorder or between simplicity and complication.

In recent years, studies have shown that complexity, regularity and stability can be usefully quantified by means of such nonlinear indicators as sample entropy (SampEn), fractal dimension (FD), and the Lyapunov exponent (LyE). All these indicators are calculated on the basis of the signal received from platforms during the center-of-pressure (CoP) measurement in anterior-posterior and medio-lateral direction. SampEn is an

entropy measure describing the irregularity of a time-series signal. Lower SampEn values indicate that a signal is more regular and predictable, which may be associated with less complexity of structure [14]. FD, in turn, assesses structural changes in signal properties – higher FD values describe better postural control [8]. LyE identifies the presence of chaos in the system under study. It evaluates the speed of postural reaction to external disturbances (sways, destabilization). Positive LyE values within the range of $0 < LyE < 1.5$ characterize healthy, young individuals [12]. The higher the LyE values, the more flexible the system. Lower values attest to greater rigidity of the postural system, meaning lesser reactivity to destabilizing stimuli [24].

Seeking to better understand the complexity of balance control, various constraints or difficulties are applied in experimental trials, meant to stimulate the organs responsible for maintaining balance [18]. The most common such biomechanical constraints include: elimination of visual feedback, reduction of the support surface area, and dual tasks. Such constraints have most often been studied during static conditions; studies assessing stability under dynamic conditions have appeared much less frequently [4], [37]. Dynamic balance involves motion and can be defined as the body's maintenance of equilibrium under conditions causing the center of gravity to move in response to muscular activity [21]. To maintain balance while being active requires dynamic balance, due to the divergent effects of gravity, momentum, ground reaction forces and muscle forces on ankle motion from an unstable, slanted or irregular surface. Therefore, measures capable of assessing dynamic balance, rather than static balance, are needed to better understand proprioceptive deficits.

One common method that has been used to perturb balance is standing on a compliant surface, such as a foam block [27]. Such conditions cause a mechanical perturbation, due to the decreased ability to exert corrective movements on compliant surfaces (reducing the effectiveness of ankle torque required for postural stabilization). However, the physical properties of such foam blocks can vary considerably, which may significantly distort the results [17]. For this reason, the Biodex Balance System SD instrumental tilting platform (Biodex, Shirley, NY, USA) was developed in order to provide an objective assessment of dynamic postural stability.

To sum up, although researchers have devised many means for evaluating postural control, ranging from functional tests all the way to platform devices that operate in static and dynamic conditions, the topic of postural control assessment remains far from fully resolved. For

this reason, technological problems have been set aside in recent years, in favor of calculation methods. The nonlinear parameters listed above have been successfully applied in evaluating postural control in healthy individuals of various age groups [29], in individuals with disorders [28], under varying visual feedback conditions [33] and varying foot position conditions [19]. As of yet, however, there is no report in the literature using nonlinear parameters to evaluate postural control in 3D space in healthy adults on an unstable surface. The aim of this study, therefore, was to assess the complexity of postural control in healthy adults during bipedal standing on an unstable surface in eyes-open and eyes-closed trials, in particular using three nonlinear indicators: sample entropy (SampEn), fractal dimension (FD), and the Lyapunov exponent (LyE).

2. Materials and methods

Fourteen young adults (8 men and 6 women) participated in this study, with mean age 24.07 ± 7.32 years, mean body mass 68.57 ± 10.68 kg and mean height 174.36 ± 8.48 cm. Participants declared no musculoskeletal or neurological deficiencies. Each participant was made familiar with the procedures of measurements and submitted written informed consent before data collection started. The study protocol was approved by the Józef Piłsudski University of Physical Education ethics committee (no. 84/PB/2016).The postural stability data for each subject, located 54 cm above ground (Fig. 1), were recorded using the Biodex Balance System SD (BBS, Biodex, Shirley, NY, USA) tilting platform, which has eight springs located underneath the outer edge of the platform providing resistance to movement, i.e., regulating the stability level of the platform. The BBS system was synchronized with a motion capture system (Vicon Motion Systems Ltd, Oxford, UK) consisting of nine infra-red cameras (sampling rate 100 Hz). Vicon was employed to collect kinematics data on center of mass (CoM) displacement. Both systems were calibrated according to the manufacturers' recommendations before the trials were performed. Before measurements, anthropometric data were taken for each person. Next, 34 spherical markers were placed at anatomical landmarks according to the biomechanical model full body PlugInGait standards (Fig. 1) available within the Vicon system.

Each participant underwent three trials in the following order: bipedal standing on Biodex balance plate with eyes open (EO), with eyes closed (EC) and also a Fall Risk test (FRT) − all three with arms held
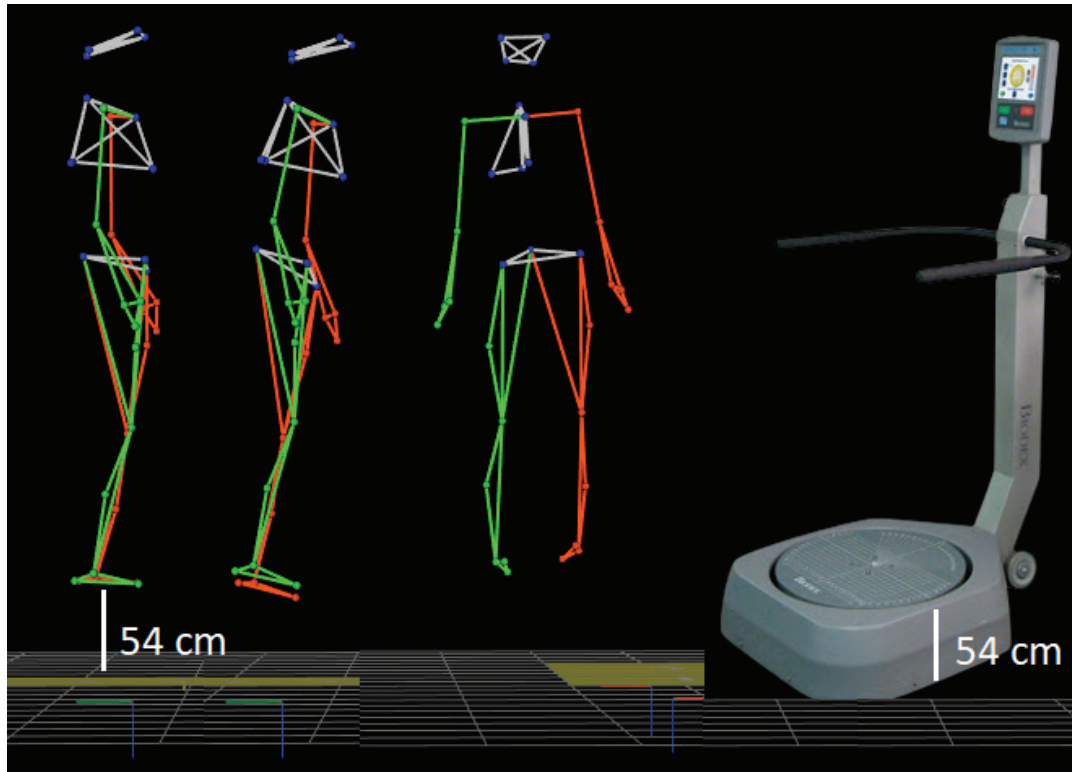
Fig. 1. Three different positions performed during the measurement.
From the left: stable position, large movement in the sagittal and frontal planes, BBS plate

downward alongside the trunk of the body. Each measurement took 20 seconds, with a 5 minute break between trials. Data collection began after the participant was standing stably, felt comfortable and was ready to begin. During the EO and EC tests, the stability of the BBS plate was set at level one (the least stable platform); during the FRT the platform changed stability from very unstable to slightly unstable (from 6 to 2). Each test was recorded once for each participant, in order to reduce the potential effects of learning and fatigue. For every one of the participants, this study was the first time they had ever encountered or been tested on an unstable platform.

From the BBS tilting platform, the following indexes were extracted: OSI (Overall Stability Index), APSI (Anterior-Posterior Stability Index), MLSI (Medial-Lateral stability Index) and FRI (Fall Risk Index).

$$\text{APSI} = \sqrt{\frac{\sum (0 - Y)^2}{\#\,\text{samples}}},$$

$$\text{MLSI} = \sqrt{\frac{\sum (0 - X)^2}{\#\,\text{samples}}},$$

$$\text{OSI} = \sqrt{\frac{\sum (0 - X)^2 + \sum (0 - Y)^2}{\#\,\text{samples}}}.$$

These measurements were calculated based on the degrees of plate tilt and are standard deviations used to assess fluctuations around the zero point. The MLSI and the APSI assess the deviations from the horizontal position on the AP and ML axes of the BSS, respectively. In contrast, the OSI is a composite of the MLSI and APSI and, thus, is sensitive to changes in both directions. The OSI has been proposed as a more reliable indicator of postural stability [1]. Lower overall scores indicate better balance and high score means poor balance.

From the Vicon system, displacements of CoM data in each direction (*x*, *y*, *z*) were exported. The model measures the CoM of 17 segments including each hand, radius, humerus, clavicle, femur, tibia, foot, thorax, pelvis, and head. For estimation of anthropometry data, the toolbox uses height, weight, leg length, knee width, ankle width, shoulder offset, elbow width, wrist width, and hand thickness. This model provides an automatic generation of the CoM 3D position after reconstruction for all body segments [26]. All subsequent calculations were made using MatLab software (MathWorks, USA). The 3D CoM path length (CoM_pl) was calculated using the following formula:

$$CoM_{pl} = \sum_{i=2}^{n} \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2 + (z_i - z_{i-1})^2}.$$

Moreover, CoM path length was calculated in each plane: sagittal (yz), transverse (xy) and coronal (xz). For each of the CoM components: x – medio-lateral (ML), y – anterior-posterior (AP), z – proximal-distal (PD), three nonlinear indexes were calculated: sample entropy (SampEn), the Lapunov exponent (LyE) and fractal dimension (FD) (these three nonlinear indexes were chosen as the only ones widely used in the literature to assess CoM displacement).

SampEn is the negative natural logarithm of the conditional probability that a dataset of length N, having repeated itself within a tolerance r for m points, will also repeat itself for $m + 1$ points, without allowing self-matches: $SEn(m, r, N) = -\ln\left(\dfrac{A^m(r)}{B^m(r)}\right)$. B represents the total number of matches of length m while A represents the subset of B that also matches for $m + 1$. For calculating the SampEn, MatLab codes obtained from the Physionet tool [13] were used, with "default" parameter values: $m = 2$ and $r = 0.2*$ (standard deviation of the data).

LyE was calculated to detect chaotic system dynamics, using the following equation: $d(t) = Ce^{\lambda t}$, where $d(t)$ is the average divergence at time t and C is a constant that normalizes the initial separation [31]. A positive LyE value is often considered a necessary condition for the presence of chaos in a given system. If LyE is zero, it means the system is conservative (i.e., there is no dissipation). If the system is dissipative, the LyE value is negative.

FD was calculated using Higuchi's algorithm [15]. Higher FD values are associated with greater complexity of a time-series.

Statistical analysis was performed using the Statistica software (StatSoft, PL), with the p-value set at 0.05. Normality of the measured and calculated data distribution was assessed using the Shapiro–Wilk test. For linear indexes (CoM path length variables, OSI, APSI, MLSI and FRI) the EO and EC conditions were compared using the t-test in order to detect significant differences. Moreover, a one-way ANOVA was performed to test differences between the stability indexes OSI, APSI and MLSI. A factorial ANOVA was used to check whether the disabling of visual feedback and the direction of movement as well as the interaction of these two factors significantly affect changes in nonlinear parameters. A post-hoc analysis was performed using Tukey's HSD test. Application of Shapiro–Wilk's test indicated that all the analyzed parameters showed normal distribution.

3. Results

3.1. The impact of visual feedback on linear parameters

Application of the t-test indicated statistically significantly ($p = 0.0001$) higher values for OSI, APSI, MLSI, FRI and CoM_pl, CoM_transverse, CoM_sagittal, CoM_coronal while standing with disabled visual feedback (Table 1). The one-way ANOVA for the stability indexes (OSI, APSI, MLSI) produced a significant difference among the indexes ($F(4, 76) = 22.325$, $p = 0.0001$) with post-hoc testing revealing that MLSI was significantly smaller than either APSI and OSI, while standing both with eyes open (EO) and with eyes closed (EC). Moreover, the one-way ANOVA for the CoM path length variables produced a significant difference ($F(6,102) = 4.116$, $p = 0.0009$). The post hoc test revealed that the CoM_pl was significantly longer than CoM_sagittal for the EO condition, whereas CoM_pl was significantly longer than CoM_coronal and CoM_sagittal for the EC condition.

Table 1. The mean and standard deviation of Biodex indexes and CoM path length variables during tests and the norm for age group; * marks statistically significant differences ($p < 0.05$)

Index	Eyes open (EO)	Eyes close (EC)	Norms for (17–35 y.o.) age group
CoM_pl [cm]	268.64 ± 91.64	1345.97 ± 278.63*	–
CoM_transverse [cm]	251.48 ± 78.89	1188.81 ± 227.17*	–
CoM_sagittal [cm]	182.88 ± 77.53	1000.14 ± 237.39*	–
CoM_coronal [cm]	192.57 ± 65.18	959.95 ± 239.17*	–
OSI	2.01 ± 0.87	14.56 ± 1.94*	2.0–5.8
APSI	1.45 ± 0.66	9.62 ± 1.97*	1.9–5.5
MLSI	1.09 ± 0.46	8.59 ± 1.73*	1.0–2.6
FRI	1.37 ± 0.51	9.03 ± 2.22*	0.7–2.1

Note that the mean values of the BBS platform indices calculated for the eyes-open condition were within the lower limits of the norm for a given age group, but disabling visual feedback significantly worsened the results. The mean values of the BBS platform indices for the eyes-closed condition were twice (OSI, APSI) and in some cases (FRI) four times higher than the upper limits of the norm.

3.2. The impact of visual feedback and direction on nonlinear parameters

Application of the factorial ANOVA and post-hoc Tukey HSD test showed a significant effect of visual feedback, direction and the interaction effect (visual feedback *x* direction) on postural stability assessed with nonlinear parameters.

The main effect of visual feedback was significant ($F(3, 76) = 28.747$, $p = 0.0001$) for all nonlinear parameters. SampEn, FD and LyE values were significantly higher during trials with eyes closed compared to those with eyes open (Figs. 2A–C).

The main effect of sway direction was also significant ($F(6, 152) = 31.096$, $p = 0.0001$). SampEn and FD values were significantly higher in the PD direction compared in the ML direction. Opposite results were obtained for LyE; here the values were the highest for the ML direction and the lowest for the PD direction (Figs. 2D–F).

The interaction effect (visual feedback *x* direction) was significant ($F(6, 152) = 8.8961$, $p = 0.0001$). Comparison of SampEn and FD values calculated in the individual directions clearly shows significantly higher values of both coefficients for the PD direction, in both the eyes-open and eyes-closed conditions. For SampEn, the highest values were recorded in the PD direction, both with and without visual feedback (SampEn_EO_PD = 0.05 ± 0.015, SampEn_EC_PD = 0.09 ± 0.02). The SampEn_EC_PD values were significantly higher than the other combinations of visual feedback and direction (Fig. 3D). However, SampEn_EO_PD was also significantly higher than SampEn_EO_AP. Much the same behavior was observed for FD. Its highest values were recorded in the PD direction in the eyes-closed and eyes-open conditions (FD_EC_PD = 1.26 ± 0.06, FD_EO_PD = 1.15 ± 0.05). The FD_EC_PD value was significantly higher than the other combinations of visual inspection and direction (Fig. 3D); however, the FD_EO_PD value was significantly higher than the FD_EO value in the AP and ML directions. Additionally, significantly higher values of FD_EO_PD were recorded in relation to the test with eyes closed in the AP and ML directions (FD_EC_AP and FD_EC_ML). The opposite tendency was noted for LyE, where both with eyes open and eyes closed the lowest values were observed for the PD direction (Figs. 3A–C). In both eyes open and eyes closed conditions, the LyE_ML values were significantly higher than in the other directions of sway.
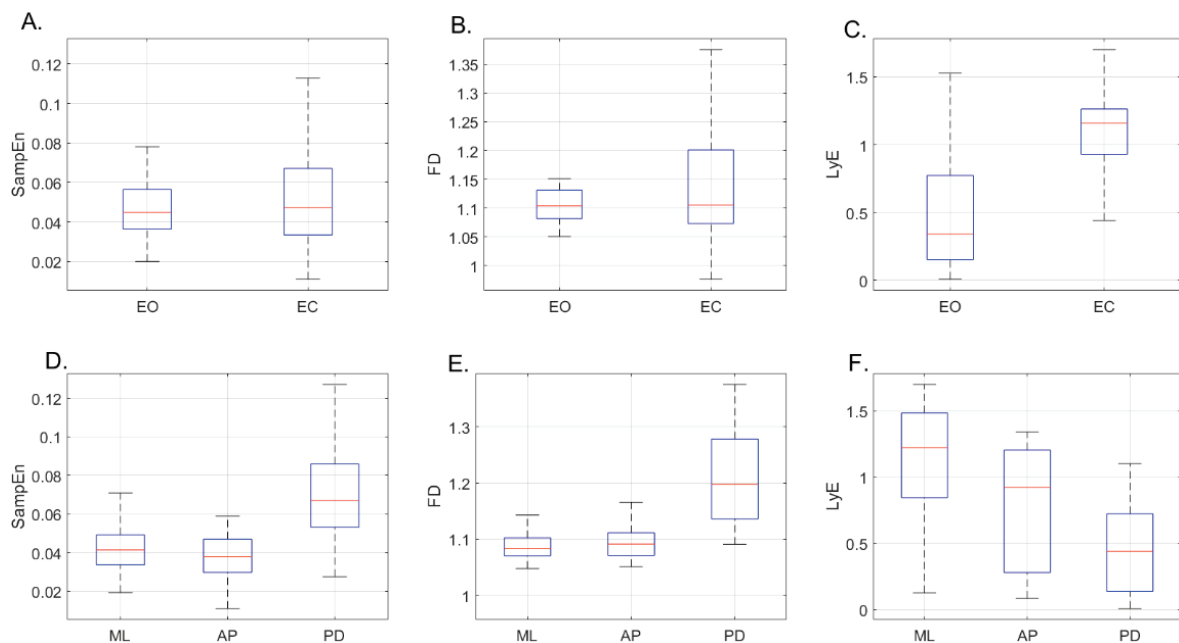

Fig. 2. The main effect of visual feedback and direction for nonlinear parameters: A, D – Sample Entropy; B, E – fractal dimension; C, F – Lyapunov exponent. The central mark indicates the mean, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points

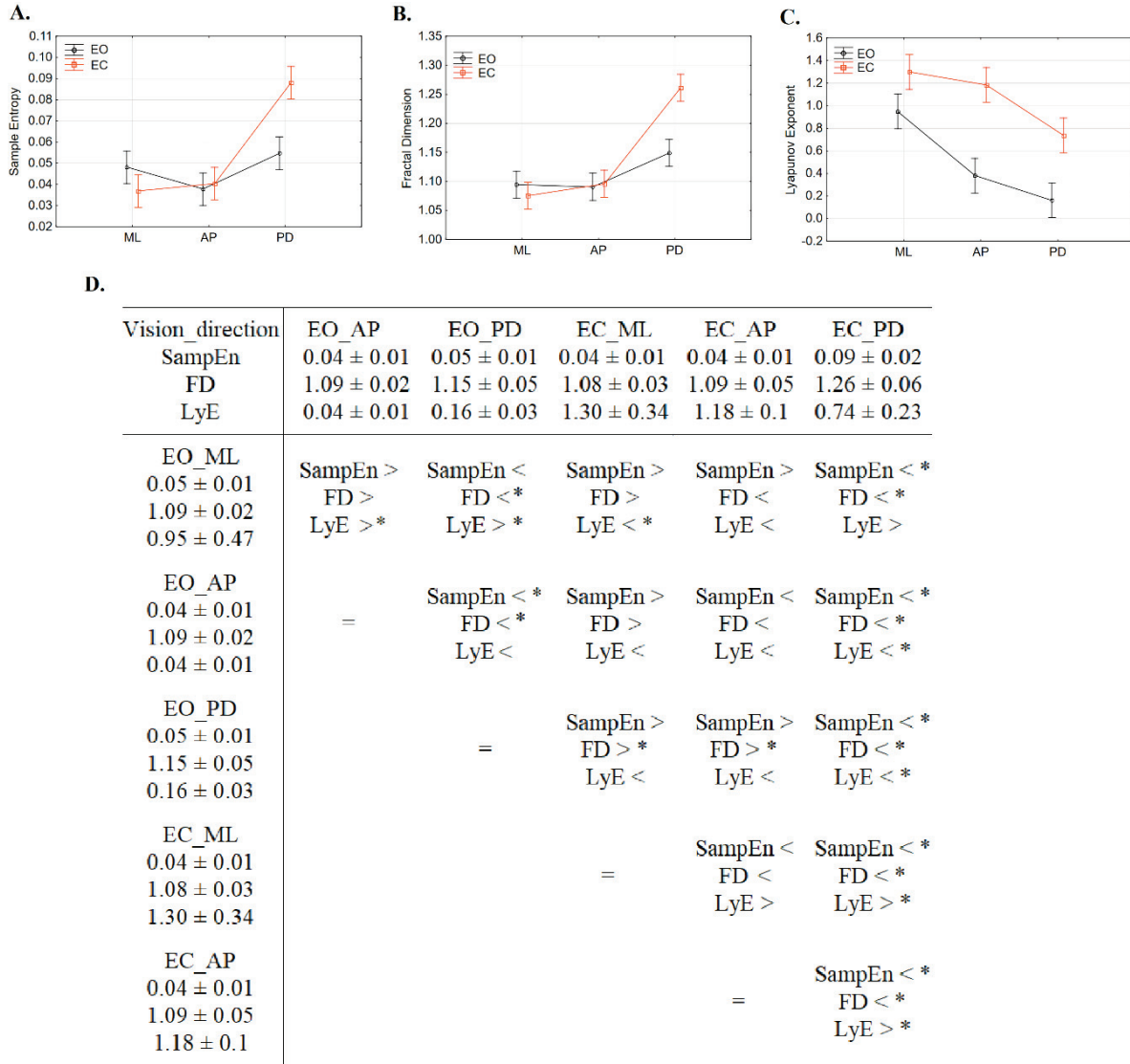| Vision_direction	EO_AP	EO_PD	EC_ML	EC_AP	EC_PD
SampEn	0.04 ± 0.01	0.05 ± 0.01	0.04 ± 0.01	0.04 ± 0.01	0.09 ± 0.02
FD	1.09 ± 0.02	1.15 ± 0.05	1.08 ± 0.03	1.09 ± 0.05	1.26 ± 0.06
LyE	0.04 ± 0.01	0.16 ± 0.03	1.30 ± 0.34	1.18 ± 0.1	0.74 ± 0.23
EO_ML 0.05 ± 0.01 1.09 ± 0.02 0.95 ± 0.47	SampEn > FD > LyE >*	SampEn < FD <* LyE >*	SampEn > FD > LyE <*	SampEn > FD < LyE <	SampEn <* FD <* LyE >
EO_AP 0.04 ± 0.01 1.09 ± 0.02 0.04 ± 0.01	=	SampEn <* FD <* LyE <	SampEn > FD > LyE <	SampEn < FD < LyE <	SampEn <* FD <* LyE <*
EO_PD 0.05 ± 0.01 1.15 ± 0.05 0.16 ± 0.03		=	SampEn > FD >* LyE <	SampEn > FD >* LyE <	SampEn <* FD <* LyE <*
EC_ML 0.04 ± 0.01 1.08 ± 0.03 1.30 ± 0.34			=	SampEn < FD < LyE >	SampEn <* FD <* LyE >*
EC_AP 0.04 ± 0.01 1.09 ± 0.05 1.18 ± 0.1				=	SampEn <* FD <* LyE >*

Fig. 3. The interaction effect (visual feedback x direction) for nonlinear parameters: A – sample entropy,
B – fractal dimension, C – Lyapunov exponent, D – table of dependencies for nonlinear parameters:
mean values and standard deviations, where: * – statistically significant differences, $p < 0.05$, EO – eyes open,
EC – eyes closed, AP – anterior-posterior, ML – medial-lateral, PD – proximal-distal axis

4. Discussion

The aim of this study was to assess the use of nonlinear parameters to evaluate the complexity of dynamic posture control in healthy adults during bipedal standing on an unstable surface, comparing eyes-open and eyes-closed trials. Delignieres and Marmelat [7] emphasize that a complex system is composed of a huge number of infinitely entangled components, which cannot be decomposed into elementary components. Each element within the system is dependent on the other elements, and each level is dependent on the other levels. Interactions between components are more important than the components themselves. Thus, when as-

sessing postural control, researchers strive to stimulate all the systems involved in guiding postural control by scaling the difficulty of tasks. Most often, authors constrain visual feedback, then add a task reducing the support surface area, asking study participants to stand on one lower limb with visual feedback enabled or disabled [29]. Other difficulties consist in adding dual tasks that distract the subject from the motor activity being performed. Some studies also included an unstable surface (i.e., foam blocks). In the last decade and a half, the Biodex Balance SD mobile platform has appeared, giving the possibility of assessing postural stability and the risk of falling. In many studies, however, stability assessment appears to be limited only to linear parameters, which fail to reflect com-

plexity, in the sense of the system's flexibility and capacity to adapt to the environment. The assessment of postural stability on an unstable surface with visual feedback enabled and disabled, as undertaken in our study, not only allowed for the assessment of postural stability in 3D space, but also evaluated the reaction to a new, unfamiliar challenge for the body, as the participants were encountering such a situation for the first time.

Taking the CoM path length variables into account, we found that closing the eyes resulted in a five-fold increase, on average, in the values of these parameters, with the smallest such increase being recorded for the transverse plane (4.72 times), and the highest for the sagittal plane (5.47 times). It is noteworthy that when using traditional 2D measurement methods, disabling visual feedback did not cause such a rapid increase in the CoP path length value. The values of this parameter increased 1–3 times on average [25], [32], [33]. It is worth noting that this difference may result from the nature of both values. The CoP results from the foot pressure distribution on the ground. The CoM is the point position in space. The nature of both values suggests that the range of changes will be different. The main disadvantage of the force analysis platform providing the CoP measure is that it measures the secondary consequences of swaying movements, not the movements themselves [34]. Significantly higher values for the eyes-closed condition were also recorded for all Biodex indices: OSI, APSI, MLSI and FRI. However, the FRI values in the eyes-closed condition were four times higher than the upper normal range, which suggested a high risk of falling. This suggests that visual information about the surrounding environment greatly affects the motor control strategy. Such a conclusion is fully borne out when we look at the behavior of nonlinear measures: sample entropy, fractal dimension and the Lyapunov exponent all exhibited significantly higher values in the trials with eyes closed. Such a result differs from the general schemas found in the literature, where for eyes closed conditions the sample entropy usually exhibited lower values for a group of healthy participants [10], [30], patients [28] and athletes [35], which was interpreted as an increase in signal regularity. It is worth adding that the above-mentioned studies analyzed the behavior of the CoP signal. Corriveau et al. [6] have shown that CoP movements may successfully stabilize the CoM. However, in our study, closing the eyes caused the analyzed signal to be significantly more irregular and jagged, as was additionally confirmed by higher FD values. Higher FD values for eyes-closed as opposed to eyes-open conditions are typical in healthy people

[36], people with disabilities [2] and people with injures [9]. According to Cimolin et al. [5], a significant change in FD may indicate a change in control strategies for maintaining a quiet stance. This finding was supported by the high LyE values under eyes-closed conditions (Fig. 2C). A higher LyE points out to the capacity for a more rapid response of balance control in different body movements [23]. Higher LyE values under eyes closed conditions have also been reported in studies assessing young people [11] and older individuals [29].

As for the main effect of direction, we found that SampEn and FD values were significantly higher in the proximal-distal direction as compared to the AP and ML directions. This finding suggests that the movements along the PD axis were highly chaotic and complex, which may have been triggered by the newly-encountered situation for the body as well as possibly greater joint mobility in the sagittal plane (and, therefore, along the PD axis). In addition, the presence of low LyE values in this direction indicates difficulties in adapting to the environment [20], which could be explained by the increased risk of falling, shown by a higher FRI index.

As for the interaction effect (visual feedback *x* direction), it is worth emphasizing that SampEn and FD exhibited significantly higher values for the PD direction, in both eyes open and eyes closed conditions, compared to the other combinations of visual feedback and direction. The increased SampEn and FD in the PD direction indicate more unpredictable and unstructured movement solutions. The opposite tendency was noted for LyE, where the lowest values were observed in the PD direction, both for eyes open and eyes closed. In both the eyes-open and eyes-closed conditions, the LyE_ML values were significantly higher than in the other directions of sway. The proximal-distal direction in the tandem standing trial was characterized by a decrease of the LyE value and an increase in the values of SampEn and FD, under both eyes open and eyes closed conditions. This fact may suggest that participants applied more rapid changes between movement solutions in the PD direction and the position information from previous completed movements were no longer influenced the execution of current movements.

This study looked at dynamic postural control in healthy young adults so that we can presume that they had large capacities for adaptation and flexibility. This is why, despite the large FRI values, no fall occurred during the trials. The architecture of healthy complex systems provides for protection against possible deficiencies and for stability to be maintained despite external

perturbations, while permitting the emergence of innovative solutions when faced with a novel problem [7].

The low LyE and high SampEn and FD values in the PD direction found in this study under both eyes-open and eyes-shut conditions may indicate that the task was relatively difficult for the subjects and demanded the engagement of all systems guiding postural control, which meant that the motor control strategy was significantly altered in order to maintain stable upright balance.

5. Conclusions

The results of tests of healthy young people presented in this paper describe and define postural control that is correct and efficient; as such it may serve as a guideline or indicator for subsequent researchers, as a point of reference for comparison with individuals with dysfunctional postural control. Our study indicates that linear and non-linear measures should be used together, as each of the proposed indexes assesses a different element of postural control.

This study added a factor absent in traditional studies – namely, the possibility of movement along the PD axis, which proved to be an important addition. The unstable surface used in the study creates such conditions that the projection of the CoM is not perpendicular to the surface, but rather set at a certain, constantly changing angle. Therefore, to avoid falling, the whole organism must adapt to these conditions. Our results indicate that the system adapts via a strategy of activating the ankle joint (Fig. 1), followed by a secondary strategy of activating the hip joint, or more precisely pelvic movements – because given the test setup the other joints generally could not move (i.e., the person examined had no possibility to make bending movements in the knee joint).

Our examination of the behavior of the CoM in the PD direction provides new information which may be challenging to explain and clearly interpret at this point in time, given the lack of such studies in the existing literature. Therefore, we conclude that future studies should also take this third plane of analysis into account using non-linear parameters, in order to more reliably analyze postural control in patients. Perhaps further studies that analyze a group of participants at greater risk of falling or suffering from a disease that degrades postural stability would yield more information and a better picture of how to interpret accurately, not only from a mechanical point of view, such high values of SampEn and FD in the PD direc-

tion. Indicating the limitations of this research, it seems that they should be done on a larger number of people.

Acknowledgments

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