Acta of Bioengineering and Biomechanics
Vol. 26, No. 2, 2024

Original paper
DOI: 10.37190/ABB-02422-2024-02

sciendo

The impact of external perturbations on postural control

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Purpose: External factors can disrupt postural control, but the intricate workings of the postural control system enable an appropriate response. This study seeks to assess how external perturbations affect postural control. *Methods*: Twenty women participated in study, which consisted four trials involved quiet standing and experiencing induced perturbations by being struck with a boxing bag from the back, right, and left sides, respectively. The center of pressure (CoP) path length was recorded for each of the mentioned trials. Sample Entropy (SampEn), Lyapunov Exponent (LyE), and Fractal Dimension (FD) were computed for the CoP time series, separately for the anterior-posterior (AP) and mediolateral (ML) directions. The nonparametric Friedman ANOVA with Dunn-Bonferroni post-hoc analysis was employed to investigate the influence of external perturbations on both linear and nonlinear parameters on postural control. *Results*: The post-hoc analysis showed for LyE_AP_quiet (1.02 ± 0.18) significantly higher values than for LyE_AP_right (0.92 ± 0.22) and significantly higher for LyE_AP_left. Lyapunov Exponent was the parameter that differentiated the most between samples. *Conclusions*: The greatest number of significant differences between samples were demonstrated by the Lyapunov Exponent. This non-linear parameter should be used to evaluate various perturbations during upright position in healthy subjects.

Key words: *external perturbations, nonlinear measures, Sample Entropy, complexity*

1. Introduction

Postural control is a complex, multicausal phenomenon described as stochastic and chaotic motions [23]. The Central Nervous System (CNS) is responsible for controlling human posture by integrating information from the vestibular, proprioceptive and visual systems [17], [24]. When postural disturbances occur, sensory systems detect deviations from the upright position, initiating immediate torque responses in the ankle and hip joints. Subsequently, adjustments in kinematics and muscle responses are made based on the direction and intensity of the perturbations [14], [19]. Researchers use a variety of external stimuli to study the perturbation responses and feedback control of human postural balance [4]. Platform translations, alterations in the physical and visual environments, virtual reality simulations, mechanical perturbations as well as pulls and tugs are commonly employed to destabilize subjects and study their postural behaviors [11]. Lee et al. [22] demonstrated that the place of application of the unloading perturbation significantly affects the postural responses. Unloading perturbation in the context of postural control is an experimental method used to analyse the body's response to a sudden change or removal of support load or external force acting. This technique involves the abrupt withdrawal of support or reduction of supporting force, enabling the study of how efficiently and quickly the CNS responds to maintain body stability and equilibrium [21]. The perturbation applied higher up the body induces greater changes in trunk inclination, internal moments and back muscle activity than the lower perturbation [21]. Moreover, the postural control strategies depend on the direction and degree of perturbation [20]. Examining the period before and just after the destabilization can visualize how the subjects respond to disturbances, control their posture and give insights into sensorimotor control of balance

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Received: March 24th, 2024
Accepted for publication: June 11th, 2024

[13]. Postural sway size is often considered an indicator of instability, but novel studies deviate from these interpretations, characterizing the amount of sway as an individual trait [33]. Therefore, in recent years, nonlinear measures have seen increased use in assessing postural control, including Fractal Dimension (FD), Sample Entropy (SampEn) and Lyapunov Exponent (LyE) [16], [27], [30], [36]. SampEn, a prevalent entropy measure, quantifies a signal's regularity [7], [29]. Lower SampEn values indicate a more regular and predictable signal, reflecting reduced structural complexity [16], [25], [27]. It can imply an inefficiency in adapting to new environmental changes [27]. Another significant nonlinear measure is the Lyapunov Exponent (LyE). As a well-defined tool characterizing chaotic signal behavior, it assesses the robustness of the human motor system against perturbations [32]. A positive value is necessary and sufficient to indicate chaos within the system [6]. Higher LyE values suggest a healthy system capable of reacting quickly and efficiently to destabilizing stimuli, thereby improving balance control [22]. Conversely, a low LyE value indicates system rigidity, an inability to adapt to external factors and poorer balance control [24]. FD indicates the complexity of the CoP signal describing its shape [6], [8]. In characterizing the complexity of the CoP signal, FD describes the activity of physiological signals and their self-similarity. A change in FD values may indicate a change in postural control during standing [6]. The most appropriate algorithm for calculating fractal dimensions for biological signals is the Higuchi algorithm. This algorithm does not depend on the binary sequence and is less sensitive to noise [6]. Multiple groups, including patients, athletes, healthy individuals and the elderly, have been assessed in various postural tasks using nonlinear measures [18]. However, existing literature lacks studies analyzing perturbations using nonlinear measures. Therefore, the aim of this study was to examine the Center of Pressure (CoP) signal immediately after perturbations occurred, employing both nonlinear and linear measures during eyes-closed conditions.

2. Materials and methods

2.1. Participants

Twenty healthy women participated in the study, and the subjects' characteristics are summarized by the following mean and standard deviation values: age, 24.35 ± 1.57 years, body height, 172.05 ± 7.56 cm, body weight, 65.60 ± 11.34 kg. Each participant provided written informed consent and was recruited based on inclusion and exclusion criteria. Inclusion criteria for participants were as follows: 1) no muscular or neural diseases; 2) no injuries or diseases in the last 5 years; 3) being engaged in physical, recreational activity three times a week. Exclusion criteria were: 1) injury or disease in the last five years; 2) bad physical condition (evaluated subjectively on the day before and day of the trial). Additionally, all participants declared having a dominant right leg. Leg dominance, according to Promsi [26], was defined as the preferred leg for kicking a ball. This study, approved by the University Institutional Review Board under the reference number SKE01-09/2020, adhered to ethical guidelines and principles outlined in the Declaration of Helsinki. Participants were fully informed about the study's objectives and procedures before involvement.

2.2. Procedures and data preparation analysis

Four balance measurements without visual control were conducted: standing barefoot – quiet stance (quiet), standing barefoot with perturbation applied from the back (back), standing barefoot with lateral perturbations from the right side (right), and from the left side (left). Data collection began after participants confirmed feeling stable and prepared. Each trial lasted 30 seconds. In trials involving perturbation, the punchbag's hit was in the fifth second. Participants were informed before the experiment about the expected perturbation but not about the precise timing. There was a 1-minute break between each trial. Throughout data collection, participants stood with their feet shoulder-width apart on the force platform adjacent to the punchbag, maintaining 0 cm between their shoulder and the bag. Before lateral perturbation trials, participants positioned their arms against the punchbag. For the trial involving a back perturbation, participants initially placed the upper part of their back (between the shoulder blades) against the punchbag. Subsequently, the bag was attached to a cable linked to the wall. The punching bag, suspended by a chain, measured 302 cm from the attachment point to the ground (y). It weighed 40.5 kg, had a circumference of 115 cm, and stood at a height of 175 cm (x). The distance from the attachment point to the wall was 85 cm for lateral perturbation trials and 62 cm for the trial involving a back perturbation (z) (Fig. 1).

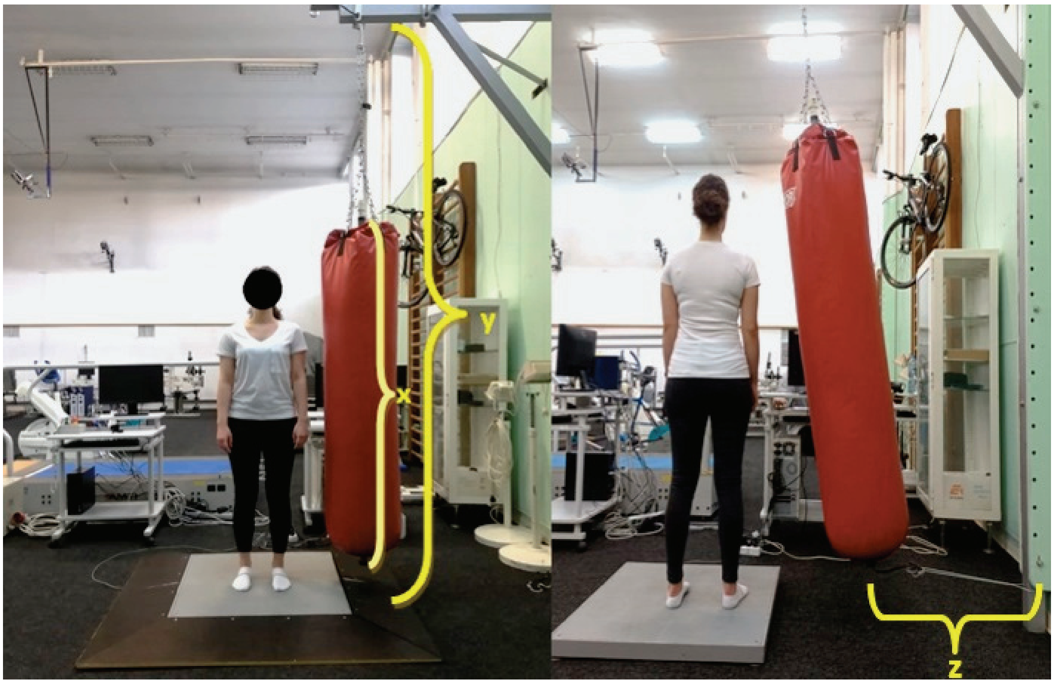

Fig. 1. The participant's position on the platform, where: x – the length of the punchbag, y – the height from the attachment to the ground, z – distance between wall and the middle of the boxing bag

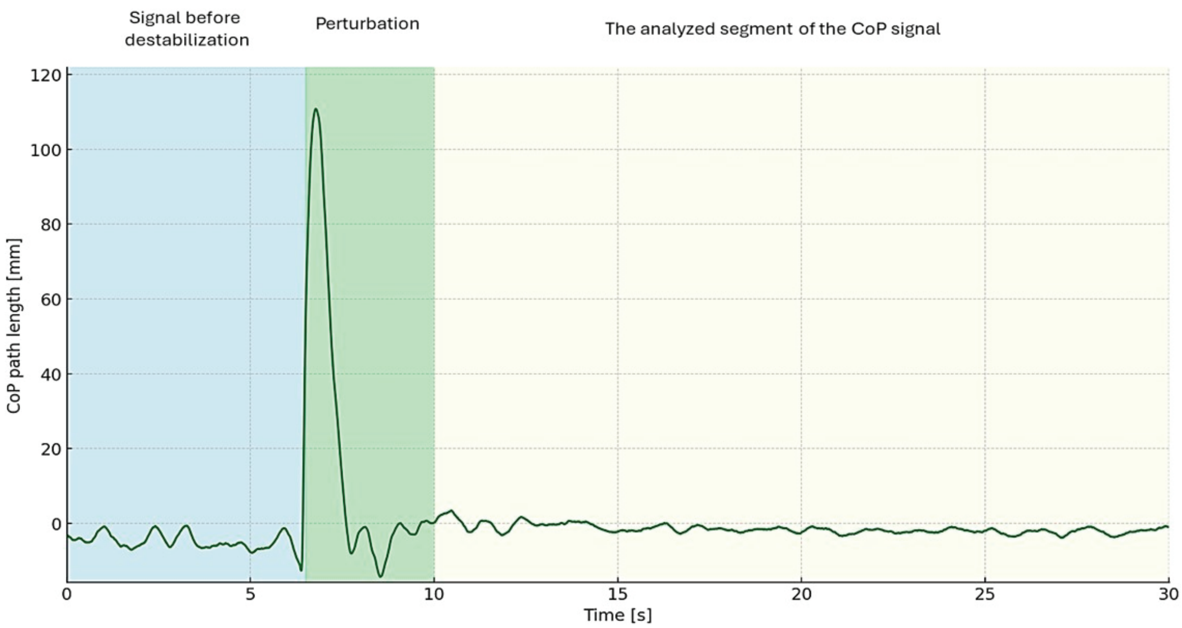

Fig. 2. Example of CoP signal waveform in the anterior-posterior direction for the back perturbation. Three parts of the signal were extracted. The first: signal before perturbation, the second – during perturbation, the third: after the perturbation – which was analyzed

In the fifth second, the punchbag was released and hit the subject in the lateral part of the arm (left and right trial) or the upper part of the spine (back trial). The impact with the bag occurred in the sixth second. The punchbag remained consistently positioned at the same distance from the participant to apply a uniform force. Participants were instructed to keep their arms relaxed by their sides, with no specific instructions given regarding muscle activity. Only one perturbation per side was performed to exclude the effect of learning and preparation. If a participant was unable to maintain an upright position or move their forefoot or heel, no second trial was conducted, and that individual was excluded from subsequent trials. The Center of Pressure (CoP) trajectories for all trials were recorded using the Sb. STANIAK force platform at a sampling rate of 100 Hz.

Subsequently, the CoP time series for the mediolateral (ML) and anterior-posterior (AP) directions were exported to MatLab R2021a software (MathWorks, Natick, MA, USA) for trimming (Fig. 2). For the quiet standing, the time series were extended from 6 to 26 seconds. After analyzing the signals for the trials with perturbations, it was decided to extend the data from 10 to 30 seconds of the measurement, after the perturbation was applied. It was observed that, after the perturbation, there was a decrease of values of CoP time series, in about 7–8 s in the time of measurement. In trials with perturbations, the time series were collected from the moment when the participant began to stabilize after the perturbation, and the signal values became steady (from 10 to 30 s) (Fig. 2). The duration of those trials was 20 s per one. The data of each participant was analyzed separately to avoid methodological errors.

2.3. Linear and nonlinear measures

CoP path length and nonlinear measures: Sample Entropy (SampEn), Fractal Dimension (FD) and Lyapunov Exponent (LyE) were calculated for the trimmed data to evaluate CoP signal dynamics using MatLab R2021a software (MathWorks, Natick, MA, USA). The CoP path length was calculated separately for each trial (CoP_quiet, CoP_back, CoP_left, CoP_back) according to the following equation:

$$\text{CoP path length} = \sum_{i=2}^{n} \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2},$$

where: x – data for ML direction, y – data for AP direction, n = 20 s. Nonlinear measures were calculated separately for the mediolateral (ML) and anterior-posterior (AP) directions. Sample Entropy (SampEn) determines the probability that a sequence of N data points, which has previously been repeated for m points within tolerance r, will repeat for an additional point (m + 1) excluding self-matches. The formula for calculating SampEn (m, r, N) is given by the negative natural logarithm of the ratio of A to B, where A is the count of sequences matching for (m + 1) points, and B is the count of sequences matching for m points. MatLab scripts provided by the Physionet resource [10] were used for SampEn calculations, employing default settings of m = 2 and r = 0.2*SD (the standard deviation) of the CoP time series [28]. In this study, FD calculations were performed using the Higuchi algorithm [11], [12]. The Lyapunov Exponent (LyE) was calculated using an algorithm originally distributed by Wolf et al. [35] in Fortran and C languages. LyE values exceeding zero indicate a chaotic system, while values equal to 0 signify stability and values below 0 suggest a tendency toward stability and constancy. Positive LyE values are crucial for confirming the presence of chaos in the system.

2.4. Statistical analysis

Statistical analysis was performed using Statistica software v.12 (Stat Soft, Tulsa, USA) with the significant p-value set at 0.05. All coefficients were evaluated for normal distribution using the Shapiro–Wilk test. The nonparametric Friedman ANOVA with Dunn–Bonferroni post-hoc analysis was used to explore the influence of external perturbation on postural stability assessed by linear and nonlinear parameters. For nonlinear parameters, the one-way ANOVA was calculated to receive the effect size and then to calculate the sample size.

3. Results

3.1. Linear parameters

The Shapiro–Wilk test results indicated that CoP path length did not have a normal distribution in all trials. The ANOVA Friedman's test for CoP path length produced a significant difference among all trials (H (3, N = 80) = 30.38, p = 0.0001) with post-hoc testing revealing that CoP path length for the quiet trial was significantly shorter (p = 0.0001) than that for the left, right, and back trials. The highest value was for CoP_right (677.00 ± 118.53 mm) and the lowest for CoP_quiet (342.71 ± 141.71 mm) (Fig. 3). The CoP path length for right trial was by 49.37.% longer than for the quiet standing, and by 1.81% longer than for the left trial.

3.2. Nonlinear parameters

During the analysis of sample size for individual parameters, values ranging from 12 to 46 participants

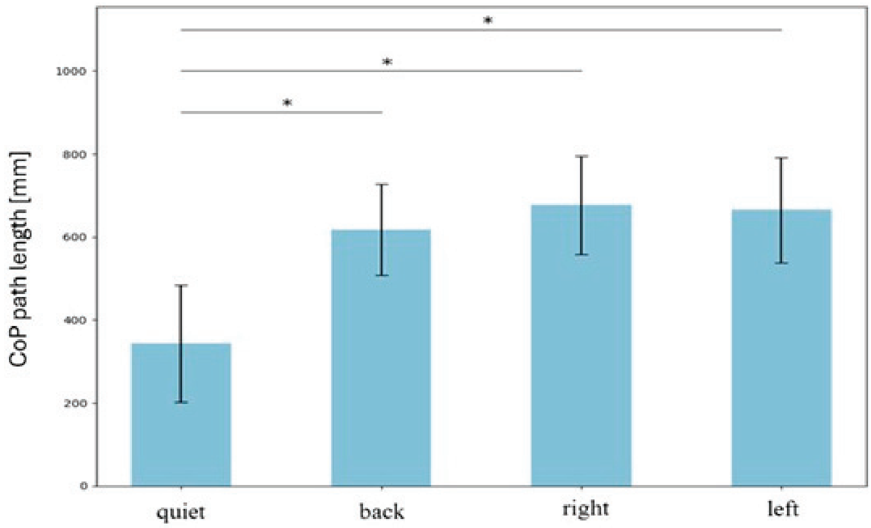

Fig. 3. Mean and standard deviations values for CoP path length during trials: quiet standing (quiet), perturbation from the back (back), perturbation from the right side (right), perturbation from the left side (left), where: * marks statistically significant differences, for $p \leq 0.05$

were obtained. Differences in the obtained sample size values may result from variations in the level of significance, test power and effect size for each parameter.

The Shapiro–Wilk test showed that SampEn_ML_back, SampEn_AP_back and SampEn_AP_left did not have a normal distribution. The highest SampEn_ML was for quiet standing and the lowest for perturbation from the right side (Table 1). The highest SampEn_AP value was observed during quiet standing, while a value lower by 33% was recorded during the back trial. One-way ANOVA revealed significant differences in

Table 1. Mean and standard deviation values for nonlinear measures during trials: quiet, back, right, left, and statistically significant differences between trials, where: ML – medial-lateral direction, AP – anterior-posterior direction, p – level of statistical significance, $p < 0.05$

Quiet	Back	Right	Left	Statistically significant difference
SampEn_ML [–]				
0.112 ± 0.06	0.080 ± 0.05	0.051 ± 0.02	0.052 ± 0.01	quiet > left, $p = 0.0001$ quiet > right, $p = 0.0001$
SampEn_AP [–]				
0.061 ± 0.03	0.041 ± 0.03	0.044 ± 0.02	0.052 ± 0.03	quiet > back, $p = 0.0258$
FD_ML [–]				
1.267 ± 0.09	1.320 ± 0.09	1.204 ± 0.08	1.212 ± 0.07	back > right, $p = 0.0002$ back > left, $p = 0.0002$
FD_AP [–]				
1.212 ± 0.07	1.208 ± 0.04	1.278 ± 0.09	1.294 ± 0.1	quiet < left, $p = 0.0006$ back < right, $p = 0.0006$ back < left, $p = 0.0006$
LyE_ML [–]				
0.696 ± 0.25	0.825 ± 0.21	1.091 ± 0.18	1.112 ± 0.13	quiet < back, $p = 0.0001$ quiet < right, $p = 0.0001$ back < left, $p = 0.0001$ back < right, $p = 0.0001$
LyE_AP [–]				
1.022 ± 0.18	1.197 ± 0.14	0.929 ± 0.22	0.880 ± 0.14	quiet > right, $p = 0.0001$ quiet > left, $p = 0.0001$ back > right, $p = 0.0001$ back > left, $p = 0.0001$

SampEn_ML among four trials (F = 11.56, p < 0.0001), with a large effect size (η^2 = 0.31) and high test power (0.99), for SampEn_AP (F = 2.99, p < 0.05), with a moderate effect size (η^2 = 0.10) and test power (0.68). The ANOVA Friedman's test was used to prove a statistically significant difference. For SampEn_ML, SampEn_AP there were statistical differences amounted, respectively, H (3, N = 80) = 26.05, p = 0.0001; H (3, N = 80) = 9.27, p = 0.0258. The post-hoc analysis showed that the values of SampEn_ML_quiet were significantly higher (by 54.54%) compared to SampEn_ML_left. Comparison of SampEn_ML_quiet and SampEn_ML_right yielded comparable results. For SampEn_AP there was one significantly higher difference between SampEn_AP_quiet and SampEn_AP_back: quiet standing values were 33.33% higher than for trial with perturbation from the back (Table 1).

The Shapiro–Wilk test results show that FD_ML and FD_AP parameters did not have normal distributions. One-way ANOVA revealed significant differences in FD_ML for all trials (F = 8.55, p < 0.0001), with a substantial effect and high test power. The indicated significant differences was for FD_AP (F = 6.30, p < 0.001), with a moderate effect size (η^2 = 0.19) and high test power (0.96). Friedman's ANOVA test was used to show statistically significant differences. There were statistical differences for FD_ML and FD_AP, respectively: H (3, N = 80) = 20.02, p = 0.0002; H (3, N = 80) = 17.43, p = 0.0006. The post-hoc analysis showed statistically significant higher values for FD_ML_back in comparison with FD_ML_right, and between FD_ML_back to FD_ML_left. The value of FD_ML_back was significantly higher (by 8.78%) than FD_ML_right, and the value of FD_ML_back was significantly higher (by 8.18%) compared to FD_ML_left. Considering FD_ML, the highest value was observed during perturbations from the back (1.320 ± 0.09), while the lowest was for perturbations from the right side (1.204 ± 0.08). Regarding the anterior-posterior direction, FD_AP_left was 9.37% significantly higher than quiet trial. FD_AP_back was respectively significantly lower (by 5.46%) than FD_AP_right and 6.20% lower than FD_AP_left. The highest values was observed during perturbations from the left side (1.294 ± 0.1) and the lowest values during perturbations from the back (1.208 ± 0.04) (Table 1).

The Shapiro–Wilk test results show that LyE_ML and LyE_AP parameters did not have normal distributions. One-way ANOVA demonstrated significant differences in LyE_ML among four trials (F = 21.14, p < 0.001), with a large effect size (η^2 = 0.45) and high test power (1.0) and for LyE_AP (F = 12.56, p < 0.001), with a moderate to large effect size (η^2 = 0.33) and high test power (0.99). When examining LyE values, significant differences were observed for LyE_ML (H (3, N = 80) = 36.60, p = 0.0001) and LyE_AP (H (3, N = 80) = 26.58, p = 0.0001). Post-hoc analysis revealed that the LyE_ML_quiet value was significantly lower (by 18.53%) compared to LyE_ML_back and significantly lower than LyE_ML_right (by 48%). LyE_ML_back was significantly lower by 24.38% compared to LyE_ML_right and significantly lower by 25.80% than LyE_ML_left. LyE_ML_quiet displayed the lowest values (0.696 ± 0.25), while LyE_ML_left exhibited the highest values (1.112 ± 0.13) (Table 1). In the AP direction, LyE_AP_back demonstrated the highest values, whereas LyE_AP_left had the lowest values. Post-hoc analysis indicated that LyE_AP_quiet had significantly higher values by 9.09% compared to LyE_AP_right and significantly higher (by 13.89%) than LyE_AP_left. LyE_AP_back was significantly higher (by 22.38%) compared to LyE_AP_right and higher (by 26.48%) compared to LyE_AP_left (Table 1). The highest values was for back trial (1.197 ± 0.14), the lowest for left trial (0.880 ± 0.14).

4. Discussion

The purpose of this study was to evaluate the impact of external disturbances on postural control. Four different trials were conducted to assess postural control using different destabilizing stimuli. The first trial consisted of standing with eyes closed without perturbation. An external mechanical stimulus (being hit with a boxing bag, from the back, right, and left sides, respectively) was added to the subsequent trials. Research to understand how the central nervous system (CNS) seeks to regulate balance requires well-structured and controlled trials, including how to analyse them effectively. In recent years, nonlinear methods to assess postural control have gained popularity [18].

Commencing with the sample entropy parameter, it assesses the regularity, complexity and predictability of a biological signal [18]. This measure particularly emphasizes the automaticity of postural tasks. Higher values correspond to more automatic postural control, demanding minimal attention [29] and indicate that the system is prepared for the unexpected. As per the present study, elevated values for SampEn_ML during quiet standing indicated that this trial was effortless for participants, requiring minimal attention to the body and postural control. A similar scenario was observed for the AP direction. However, the distinction appeared in the case of perturbed trials, which had significantly lower values of Sample Entropy. These findings suggest that perturbations posed challenges for participants, resulting in a loss of control and a reduced „level" of postural control compared to standing undisturbed. In the ML direction, the lowest values were associated with the right perturbations, while in the AP direction, the back perturbation yielded the lowest value. Despite that participants declared right leg dominance the values of Sample Entropy for ML direction were quite similar (right = 0.051 and left = 0.052). Except for the directions, there was no significant difference between left and right perturbations with respect to Sample Entropy in both the ML and AP directions.

The next parameter was the Lyapunov exponent, which describes the postural response; higher values indicate the ability to respond more rapidly to balance perturbation [2]. Khayat and Nowshiravan-Rahatabad [19] showed that higher LyE values in young participants' postural signals indicate the resilience and accountability of their control system as a nonlinear, complex one. Nonlinear parameters are more discriminative and representative for determining the attitude signals of older and young participants. They are also better for discriminating postural differences during these trials. In this study, we see an increasing trend in Lyapunov values. For quiet standing, the values in the ML direction were the lowest, and for striking from the left side, the values were the highest. For the AP direction, the highest value was for perturbation from the back, and the lowest value was for perturbation from the left. This trial produced difficult conditions and caused an increase in the LyE values. It is worth adding that stimuli from the back caused the highest values in the AP direction, which could be interpreted as the fast reaction of the whole body on destabilization and effective postural control. In the anterior-posterior direction, LyE values were lower for the left and right perturbations. In the ML direction, the highest values were for left and right perturbation, so, compared to the study by Ghofrani et al. [9], the participants in the present study had low LyE values in the quiet standing position. In that study, for subjects aged 22–23 years, LyE values ranged from 1.80 to as high as 2.23 under closed-eye conditions [9]. Our results had much lower values of LyE, which amounted from 0.70 to 1.02. The LyE parameter showed the most statistical differences between samples compared to other nonlinear parameters, but there was no significant difference between left and right perturbations for AP and ML direction. Fractal dimension serves as an indicator of signal complexity, with lower values suggesting reduced complexity. In this study, FD values were above 1.0 in all trials. In the case of the ML direction, a higher and more complex, irregular trial occurred when the perturbation was applied backward. As for the previous nonlinear parameters, also for the fractal dimension, there were no statistically significant differences between right and left destabilization. It is essential to highlight that, for linear parameters (CoP path length), differences were evident only between quiet standing and various perturbations, without distinctions among types of perturbations, particularly between those applied from the back and sides. For nonlinear measures, more differences were found in differentiated responses to perturbations between those applied to the back and sides. From the above descriptions, nonlinear measures differentiate changes in postural control much better than linear path length parameter. Consequently, responses to perturbations on the left or right side pose more challenges for participants than those applied to the back.

In the literature on the subject, noteworthy are papers analyzing responses to perturbations using only linear methods. In the study by Xie and Wang [36], the authors examined twenty-two participants who were instructed to maintain balance while keeping their elbows bent at 90° and holding a metal tray in their hands. Sandbags of various weights were released and fell freely onto the tray. Two test conditions were used: known – participants were informed of the sandbag weight before each trial and unknown – participants were not informed of the weight of the sandbags in any of the trials. The authors presented a significant effect of conditions on CoP displacements. The center of pressure path length increased with load level under known conditions, but there was no significant difference for unknown conditions [36]. The highest displacements were for unknown conditions for 2 kg sandbags, and the lowest for 1 kg. The lowest displacements for known conditions were for 1 kg, and the highest for 1.5 kg [36]. This study revealed that in cases where the magnitude of perturbation was known, postural muscles exhibited more pronounced anticipatory reactions, leading to a more significant sway in body movement. It is worth noting that in the present study, participants were also aware of the presence of perturbations, which, as demonstrated, could influence the results. In the study by Blenkinsop et al. [3], twelve experienced gymnasts proficient in handstands were examined. Diverse types of perturbations, including backward (both large and small) and forward (both large and small) were generated by the platform. Their findings indicated that, during perturbed standing balance, no significant differences were observed among the different perturbation directions. This result contrasts with the present study, where differences in both linear and nonlinear parameters were observed depending on the direction of the perturbation. It is noteworthy to mention that the translations generated by a force platform had a comparatively smaller impact than a 40 kg punchbag on the participants in our study. De Azevedo et al. [5] compared postural reactions in response to external shoulder perturbations in subjects with Parkinson's disease and healthy control group. Despite the presence of the disease, the analysis revealed that CoP displacements in ML directions were significantly greater in the control group than in the Parkinson's disease group, with no statistically significant differences between the groups in AP displacements. Displacements in both groups ranged from 20 to 60 mm and were observed in the opposite direction to the original perturbation. A similar strategy was observed in studies by Santos et al. [29], [30] involving healthy subjects. It is essential to note that the mere anticipation of perturbation can induce changes in emotional state and impact standing postural control [1]. The perceived threat of postural perturbation to the torso is linked to greater trunk sway amplitude [34], velocity, forward lean, and an increase in the amplitude of the CoP signal [15]. In Sever's et al. [31] study, postural reactions to sudden horizontal perturbations were examined in Tai Chi practitioners and controls. Perturbations were applied at the height of the hips (aligned with greater trochanters), shoulders (placed at the upper sternum) and arms. The study found no significant differences between peak CoP displacements between the groups at the hip, shoulder, and arm points of perturbation. The lowest displacements were observed at the hip point for both groups, while the highest was at the shoulder point [31]. Moreover, Latash [21] found that perturbations applied below the hips are easier to respond to from a mechanical perspective since the human body resembles an inverted pendulum.

5. Conclusions

Postural perturbations affecting the body laterally modified both linear and nonlinear parameters significantly. However, perturbations from the back were more challenging, requiring a more complex response compared to those from the left or right. The limitation of this study is the absence of electromyography analysis for muscle activity. Another limitations are sample size, because study included only 20 young women, this results may not be fully generalizable to other demographic groups, such as men, older adults or individuals with different levels of physical fitness. The study analyzed short-term effects of perturbations. Further research should include long-term observations to understand the impact of repeated perturbations on postural control. In the future it will be worthy to add various, linear parameters as velocity, CoP surface area, radius and others, not only path length. The study did not consider the impact of psychological factors such as stress or anxiety, which may influence postural control. Research into these aspects could provide additional information on the reaction between emotional state and postural control. Considering the diminished effect size evident in the fractal dimension parameter, it is advisable to augment the sample size for the study cohort. Future studies would benefit from obtaining kinematic data to study body movement accurately, with particular focus on trunk and pelvic movements after perturbation. It is recommended that subsequent research extend the trial duration to facilitate a comparative analysis of the CoP signal before and after perturbation, allowing for an equivalent period within a single trial.

Acknowledgments

This research was funded by the Józef Piłsudski University of Physical Education in Warsaw, grant number UPB No. 2 (114/12/PRO/2023).

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