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Research article

Analysis of oscillations of the center of pressure in postural control

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Abstract: Posture results from intricate interactions between the central nervous system's control mechanisms, sensory integration, and musculoskeletal responses, encompassing two levels: sustaining tonic muscle activity for posture and making adjustments to maintain balance in response to disturbances. Due to its complexity, assessing posture with simple methods is challenging, necessitating the use of advanced techniques like stabilometric platforms to measure postural stability through the center of pressure oscillations, akin to an inverted pendulum concept, offering a comprehensive understanding of postural control mechanisms. Materials and Methods: The study aims to analyze the trajectory of the center of pressure (COP) in relation to the gender of the subjects, through directional indices (DI) and oscillation ratio (OR), in the process of posture maintenance. The study included a sample of 50 young subjects (21-24 years), sports practitioners, divided into two equal groups. Results: The study findings indicate that gender does not influence COP DI. However, there's a significant disparity between anteroposterior (AP) DI values (0.70) and mediolateral (ML) DI values (0.54). The results suggest a predominant reliance on AP control mechanisms for maintaining balance, regardless of gender. When visual input is absent, there's a slight increase in AP DI (0.72) and a decrease in ML DI (0.52), indicating a shift in balance strategies. In terms of OR, significant differences are observed based on gender, oscillation direction, and visual input. Female subjects exhibit higher AP OR (6.5) compared to males (5.1). Under closed eyes conditions, both genders show decreased AP OR (6.0 for females, 4.7 for males), indicating a reliance on alternative balance strategies in the absence of visual cues. Conclusion: The study highlights the complexity of postural control and empha-sizes the influence of factors like gender and visual input on postural stability metrics, providing valuable insights for further research and clinical practice. The analysis reveals that around 60% of COP oscillations occur in the AP direction, regardless of visual input changes. This underscores the critical role of AP control in maintaining balance, suggesting targeted interventions to enhance stability should prioritize this aspect.

Keywords: postural control, oscillations of the center of pressure, stabilometric platform.

1. Introduction

Posture is the position of the body and body segments in space, a correct posture aims to keep the body in balance, during movements (dynamic) and in the absence of movements (static). Posture control is ensured by numerous anatomical structures, and neurophysi logical, biomechanical, and psycho-emotional factors in direct relation to the evolution of the species [1].

Currently, two different levels are recognized in the postural control system, one level establishes the distribution of tonic muscle activity (posture), and the other is attributed to the compensation of internal or external perturbations (balance). In this study, we will consider the neuromechanical basis of posture and various concepts that have influenced numerous experimental studies and mathematical control models of human body posture. Thus, posture control is achieved through interactions between the musculoskeletal, visual, and vestibular systems. Recently, numerous studies have correlated the musculoskeletal system with postural control [2].

The unique structure and properties of skeletal muscles must be considered to understand the contribution of peripheral factors to postural regulation. In postural control, the activation of skeletal muscles to stabilize body segments, as well as the elastic properties of skeletal muscles and muscle tension are important elements. Even if muscle activity in posture control is reduced, it should be emphasized that it is not a passive process, the specific activity of neck, trunk, and limb muscles determines tension at rest, individual postural attitudes, facial expression, etc. [3].

Another key aspect of postural control involves responding to postural perturbations through anticipatory and compensatory adjustments to maintain balance. Anticipatory adjustments increase in magnitude as the perturbation becomes more significant, whereas compensatory adjustments remain consistent, determined by the required corrections. However, it's important to note that the effects of a postural disturbance may not always be completely resolved [4].

The postural control can be quantitatively assessed by analyzing the displacement of the center of mass (COM), and the center of pressure (COP), but also by measuring the electromyographic activity and the contribution of various sensory information, a quantitative assessment is made. The qualitative analysis of postural control consists of describing how postural control is organized in biomechanical and neurophysiological aspects [5].

The presence of low back pain (LBP) has a notable impact on the intricate interactions within the postural control system. Interventions aimed at managing LBP can alter the functioning of this system, potentially affecting an individual's capacity to maintain balance and stability. This underscores the importance of considering LBP and its management when evaluating and addressing issues related to postural control. This highlights the importance of considering LBP and other influencing factors when assessing postural control [6]. The relationship between motor control and low back pain (LBP) in daily activities has been a subject of frequent study. Specifically, there has been a focus on understanding how impaired postural control may affect the ability to stabilize the spine, given the high prevalence of LBP in daily activities [7].

Currently, there is no clear evidence of differences between people with and without acute LBP in terms of anticipatory and compensatory postural adjustments [8]. Conversely, the delayed onset of muscle activation in people with chronic LBP suggests that anticipatory and compensatory postural adjustments are altered in this population [9].

Postural control is frequently used to quantify the COP trajectory (stabilogram), while standing. This quantification has many important applications, and the early detection of balance and postural control disorders to prevent falls is an important aspect whose relevance increases with the aging of the population [3].

For posture examination, the most used are force platforms, which are made of a stable plate under which load sensors are positioned. The platform can be embedded in specific devices to generate instability. Stabilometry, the measurement of forces exerted on the support surface (platform) during bipedal stance, is frequently used to analyze postural stability in research and clinical practice. Stabilometry typically focuses on time series properties of the COP, representing the location of the point of projection of the support surface reaction force vector as it evolves horizontally or along two axes orthogonal, fixed on the platform, anteroposterior (AP) and mediolateral (ML). This variable reflects the manner of maintaining balance and provides a general picture of postural stability control.

The assessment of postural control by COP trajectory analysis is not a new approach, but until now there has been no consensus on the methods of processing the data obtained.

In general, the processing of COP displacement speed data has been recommended for assessing the stability of postural control [10].

The purpose of the study is to analyze the trajectory and position of the COP using the directional indices (DI) and the oscillation ratio (OR) in direct relation to the variable represented by the gender of the study participants (men, women). We believe that by quantifying the characteristics of postural oscillations based on COP signals recorded in healthy young subjects tested on the platform in the standing position with eyes open and then with eyes closed, the analysis of postural stability control can be performed.

2. Materials and Methods

2.1 Participants and Procedure

The research was conducted on a sample of 50 subjects, belonging to the statistical population called healthy young people (21-25 years old), without musculoskeletal or neurological disorders, consistent and moderate practitioners of sport (but not at the level of performance). Subjects were divided into two groups according to gender 25 female and 25 male subjects. Each participant expressed their informed consent.

The activities that formed the basis of the research were carried out within the Interdisciplinary Research Center of the National University of Physical Education and Sport from Bucharest.

The subjects were informed and instructed to observe the optimal conditions for testing and the stages of the study. Each subject received instructions regarding the position necessary for the test, respectively sitting with legs slightly apart positioned on the platform with the tips at the same level, upper limbs relaxed alongside the body, looking forward; a position as relaxed as possible to be maintained for 20 seconds with the open eyes, after a relaxation of a few seconds, in which the subject is asked to leave the platform, is followed by 20 seconds with maintaining the position with the closed eyes.

2.2 Instruments and types of evaluation

The equipment used to assess stability and body balance consists of the following modules and software PoData Balance Platform, and GPS 5.0 Software.

The PoData balance platform is a device that allows the measurement of the vector of the total force exerted during contact between the surface of the human body (usually the foot) and its surface. This device is used to determine the static balance of the human body, by measuring the displacement of the COP. The platform is equipped with four piezoelectric force sensors, each positioned in the four corners of the plate. The principle of operation is to transform a mechanical action (the force with which the subject acts on the plate) into an electrical signal without any external source of energy. The floor surface, on which the platform is installed, meets the plan-parallelism conditions imposed by the manufacturing company for precision measurements.

GPS 5.0 software is a software whose main features include processing patient and medical history data, general clinical data and examinations, body posture analysis, postural stability analysis, and footprint analysis. This software was installed on a high-performance computer, and the data obtained were processed using 9-order Chebyshev low-pass filters Cheby2 Matlab Mathworks © Natick, USA (MATLAB).

The COP trajectories were determined using the force plate within the GPS 500 stabilometry platform. Data were collected with a sampling frequency of 40 Hz. Time series of the COP were digitally filtered offline with MATLAB to an optimal frequency limit. The frequency of the filter was methodically changed in the range of 5 to 11 Hz until is most favorable COP filtering frequency was found. Then two parameters were calculated, namely the directional indices and the oscillation ratio based on the optimal filter frequency of 10 Hz.

Directional oscillation indices (DI) were defined as the ratio between the length of the anteroposterior (S_{AP}) or mediolateral (S_{ML}) direction displacement and the total COP displacement (S_{TOT}).

Measurable oscillation parameters can label instability in several categories, zero instability is the equivalent of perfect balance, and the most unfavorable category is unstable balance.

The oscillation ratio was calculated for COP - COP_{filter} relative to the path length. To achieve the goal, we used COP time series that were filtered again with a low pass filter with a cutoff frequency of 0.4 Hz of MATLAB.

The statistical processing of the data was performed using the one-way ANOVA method for independent samples to statistically examine the significant differences in the analyzed parameters between the two groups and between the two experimental conditions open eyes and closed eyes.

3. Results

The study's findings suggest that postural control is subject to influence from various factors, including non-specific low back pain and weather conditions. These influences become particularly apparent in situations with specific requirements or demands placed on the individual's balance and stability. The movement of the COP provides information for various situations in which the subject must adapt to disturbances by external forces, such as when the support surface is unstable. The data obtained by testing the subjects were centralized, and the OR and DI for statistical processing were calculated.

Table 1. Results of the amplitude spectrum for the direction index and the oscillation ratio at the frequency of 0.4 Hz ($DI_{AP/ML}$ - direction index anteroposterior/mediolateral; $OR_{AP/ML}$ - oscillation ratio anteroposterior/mediolateral)

Parameters (cm)	Group Male(M)/Female(F)	Open Eyes (OE)	Close Eyes (CE)
DI_{AP}	M+F	0.72	0.70
DI_{ML}	M+F	0.52	0.54
OR_{AP}	M	5.1	4.7
	F	6.5	6.0
OR_{ML}	M	4.7	4.0
	F	5.9	5.5

The results for directional oscillation indices were calculated and analyzed for COP variations, ANOVA statistical processing confirms a significant effect of two factors on oscillation direction $F(1.44) = 173.3$, $p \le 0.000001$, and visual input $F(1.44) = 16.5$, $p \le 0.0002$.

The gender of the subjects did not affect the DI of the COP. In both groups, the mean value of the DI in AP was significantly higher compared to the DI values in ML (0.70 by comparison 0.54, $p \le 0.000001$). The absence of visual information led to a slightly statistically significant increase ($p \le 0.004$) of DI in AP (increase to 0.72) while under the same test conditions, the ML directional index decreased slightly (approximately 4%) to 0.52 ($p \le 0.0007$). The results of processing the directional index data are shown in Figure 1.

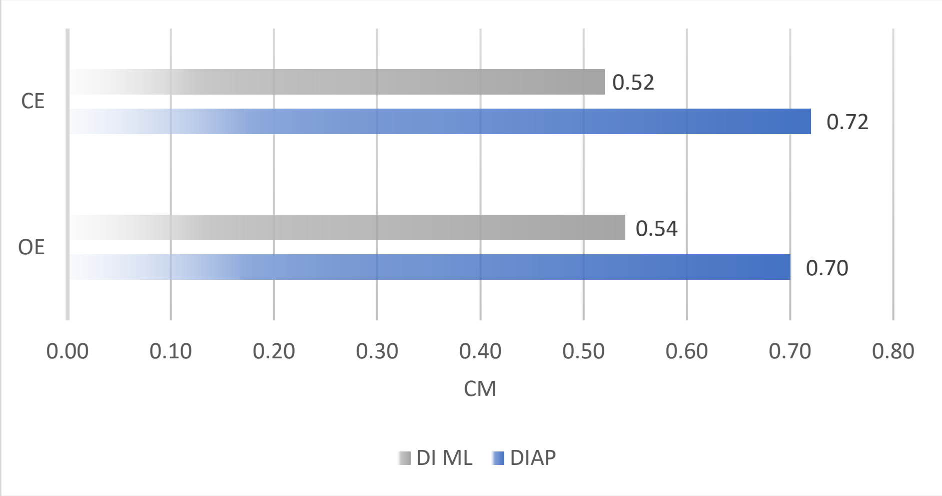

Figure 1. Directional oscillation index for anteroposterior (DI_{AP}) and mediolateral (DI_{ML}) in subjects during open eyes (OE) and closed eyes (CE) tests, frequency of 0.4 Hz

The analysis of variance did not reveal any differences in the case of directional indices. In both groups and for both visual conditions the DI remained at the same level 0.64 ± 0.08 in the AP direction and 0.64 ± 0.07 in the ML.

The results for the oscillation ratio (OR) processed with ANOVA showed significant differences depending on the type of subjects $F(1.44) = 14.8$, $p \leq 0{,}0004$, the direction of oscillation $F(1.44) = 17.3$, $p \leq 0.0002$ and the visual input $F(1.44) = 35.1$, $p \leq 0.000001$ related to the oscillation rate. For female subjects, the mean anteroposterior oscillation ratio (OR – AP) was significantly higher (6.5) compared to male subjects (5.1). Under the close eyes conditions, the average OR – AP decreased significantly in both groups and its value remained at 6.0 and 4.7 for females and males, respectively.

The mediolateral oscillation ratio (OR – ML) when measured with OE and CE was characterized by the decrease of the values from both groups. OR - ML results were 12% lower in males (5.1 by comparison 4.5, $p \leq 0.0003$). The results of the statistical analysis are shown in Figure 2.

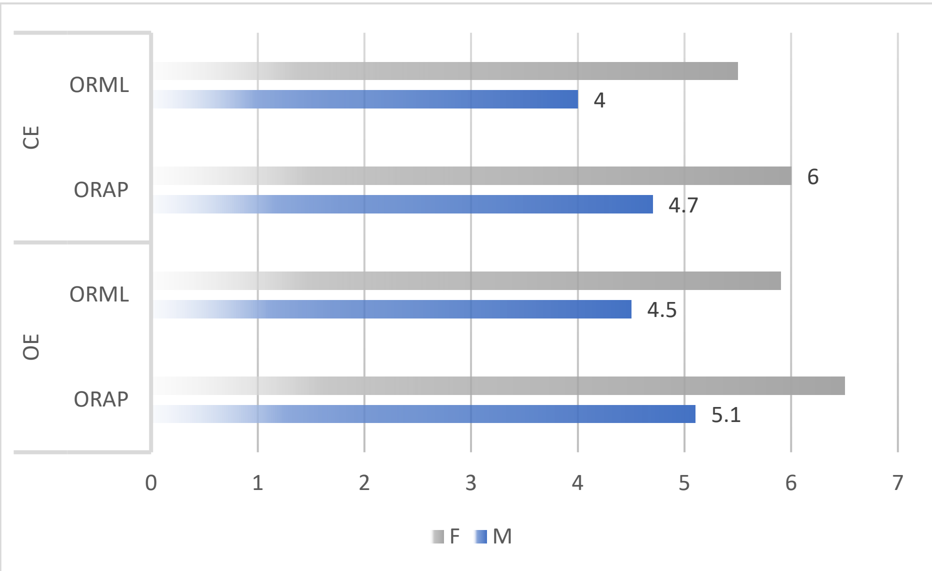

Figure 2. Oscillation Ratio anteroposterior (OR_{AP}) and mediolateral (OR_{ML}) in the male (M) and female (F) group, tested with open eyes (OE) and closed eyes (CE), frequency of 0.4 Hz

4. Discussion

The results of the study reinforce the observations of some studies, according to the context of the equilibrium point hypothesis which suggests that the equilibrium is adopted according to a migratory reference point characterized by two subsystems, conservative ramble, and operative tremble [11]. Movements in the conservative ramble subsystem reflect behavior that does not induce significant rebalancing forces, and movements around the reference point characterize the operative tremble subsystem that seeks to maintain balance [12]. The two subsystems describe two different processes in vertical position control: ramble reflects the supraspinal processes involved in movement control, while tremble reflects spinal reflexes and changes in the intrinsic mechanical properties of muscles and joints [12].

The research results were also confirmed by the fact that the directional oscillation index for AP and ML directions reached the set reliability coefficient, higher than 0.80, in the case of a test of 40 s / subject (20 s OE, 20 s CE).

Consequently, the major oscillation axis corresponds to the direction of the lowest stability and therefore the directional influence measures seem to be the most convenient for the assessment of postural stability. This proves that, normally, in healthy subjects, the oscillations in the AP are larger than the oscillations in the ML direction with a ratio of about 1.5 during both OE and CE conditions. There are also several inferences on the postural control that can be derived from an elliptical coverage of 85.35% of the oscillation surface. The elliptical shape of the COP oscillation zone reflects the shape of the stability boundaries and the eccentricity of the ellipse which allows the evaluation of the directional control of the COP.

In the proposed model, the probability of maintaining postural stability following a gravity-induced disturbance is dependent on the speed and direction in which the COM is disturbed. If the event of a change in the size of these parameters exceeds certain limits, the postural control may become unstable, and the subject would be at risk of falling.

These depend on the magnitude of the body's oscillations and the limits of stability. Our results on DI and OR are consistent with those in the literature and confirmed that in to maintain a vertical body position, the neuromuscular system must devote 50% more effort to control stability in the AP direction. The average value of the two calculated DI, whose relative contribution to the displacement of the COP in the frontal and sagittal planes shows about two-thirds of the oscillation movements (about 60%) in the direction of AP. This proportion remains unchanged even if the visual input is modified. The results show that in standing with CE, DI changes have small values, although statistically significant and similar in the two directions AP and ML.

Contrary to our expectations, both in AP and ML directions, the values of the oscillation ratio decreased when the visual input was not eliminated. This contrasts with old research with healthy adult and Parkinson's subjects that showed a significant increase in the OR under CE conditions [13,14].

In the present study, certain limits are accepted regarding how the data are processed which may influence the interpretation of the values about the speed, amplitude, COP trajectory, respectively the postural stability analysis. In this regard, we considered that the incorrect selection of two basic factors, namely analog-to-digital frequency sampling and COP data filtering can critically alter the results and the interpretation of the results. Therefore, in this study, we considered the aspect of the influence of two parameters, namely the oscillation ratio and directional indices, in the assessment of postural stability, they seem to outline the most reliable way of analyzing the COP trajectory.

Chiari et al in 2002 used a crude regression analysis, which revealed the dependence of most stabilometry parameters in COP trajectory analysis on biomechanical factors [15]. This dependence can cause data to be misinterpreted when comparisons are made. In general, a set of measurements (biomechanical factors) are recommended, that should be targeted: height, weight, foot support area, foot width, and foot opening angle. To evaluate the influence of biomechanical factors on the stabilometric parameters, multiple regression analysis was used to determine which of the biomechanical factors were correlated with the variations of each stabilometric parameter. Finally, to establish this optimal set of measurements, an iterative algorithm was applied. This algorithm is recommended for all possible regression models and suggests the optimal solution in terms of a balance between simplicity (more regressions possible) and reliability (how many regressions are needed).

Furthermore, despite the similarities observed between the values obtained when using two different protocols for standing balance, recorded on two samples of elderly people, but in which the recommendations regarding the duration of the recording were followed, at least 60 s, several repetitions; sampling frequency 100 Hz and a cutoff frequency of 10 Hz; standardizing the position of the legs on the force platform, especially when using variables that depend on the base of support.

According to Gagea (2010), most often, the regulatory system of postural balance is treated as a mathematical model of the inverted, double-jointed pendulum [16].

Dutt-Mazumder (2018) reviewed some evidence for organizing properties in dynamic postural balance and increased variability and entropy before the coupling phase transition between COM and COP [17]. Studies on the multisegmental organization of human postural control in a dynamic balance task have highlighted the aspect of COM/COP coordination, which changed from one phase to another, at a critical frequency (~0.4 Hz to 0.0 Hz) by increasing or decreasing the support surface [18].

The control of postural stability is a multidimensional dynamic process in which efficiency depends on numerous physiological and anatomical factors [19]. It seems that damage to the integrity of some physiological systems, especially in the sensory system, profoundly impacts the control of postural stability. Analysis of postural oscillations in both AP and ML directions provides important information regarding the effectiveness of the postural control system for maintaining a posture. It has been observed that the major axis of oscillation corresponds to the direction of reduced stability, and therefore directional-influenced measurements appear to be the most convenient for assessing postural stability. Numerous studies show that in healthy subjects, balance in the AP direction is greater than in the ML direction by a ratio of approximately 1.5 in both conditions: eyes open and eyes closed. Therefore, postural control analysis can be derived from an elliptical coverage of 85.35% of the oscillation surface [20]. The elliptical shape of the COP oscillation zone reflects the shape of the stability limits, and the eccentricity of the ellipse allows the evaluation of directional control. In healthy young adults, the margins of stability in AP and ML are fairly symmetrical, whereas in older adults the stability zone is characterized by significant asymmetry [13]. There is also evidence that instability along the ML direction is an important posturographic marker of impaired functional balance. Increased oscillations along the ML direction are associated with an increased risk of falls in the elderly and in Parkinson's disease patients who are prone to falls [14]. In this context, by comparing the AP and ML oscillations, it is considered that a relatively greater increase in the ML direction oscillations of the COP in a standing position without visual input may suggest a decrease in postural stability.

Limitations in any of the sensory systems responsible for maintaining balance, strongly affect the control of postural stability. This problem is frequently examined in static posturography by testing subjects standing with their eyes closed. Under these conditions, the control of postural stability works at a less optimal level than it should due to the deprivation of information from the visual system. To compensate for this shortcoming, the postural stability control needs to be reorganized accordingly to cope with the new conditions. There is growing support for the claim that postural control works optimally over a limited range of random muscle activity. Thus, in the research of our subjects, the observed decrease in the size of the oscillation ratio under closed-eye conditions may result from increased oscillations (which may suggest a decrease in postural stability) that are not fully compensated by increased muscle activity. The lack of full compensation for increased amplitude of oscillations may, however, only indicate that in healthy young subjects with robust postural stability control, such compensation may not be necessary.

A limitation of the study we consider to be the fact that we omitted the influence of anthropometric parameters (body weight and height) on postural stability. Given the inverted pendulum pattern, a higher subject has a higher oscillation amplitude. Moreover, other anthropometric characteristics, in addition to body weight, such as the length of the lower limbs, influence the oscillation characteristics. Female subjects have a relatively low mass of muscle tissue, which results in lower overall muscle strength. All these factors differed substantially in the study groups and may explain the differences observed in postural stability related to the gender of the subjects.

For patients struggling with postural issues, maintaining proper alignment is crucial for overall well-being and quality of life. While traditional methods like physical therapy are beneficial, integrating neurofeedback into rehabilitation protocols offers a personalized and innovative approach to improving posture control. This brief review explores how neurofeedback empowers patients to take control of their posture and enhance their health outcomes.

Integrating neurofeedback with physical exercises represents a promising strategy for optimizing rehabilitation outcomes in patients with postural issues. By harnessing the complementary benefits of these modalities, healthcare providers can offer personalized and effective interventions that empower patients to achieve lasting improvements in posture and musculoskeletal function. As research continues to explore the synergies between neurofeedback and physical therapy - exercises, integrated rehabilitation approaches have the potential to revolutionize posture management and enhance patient well-being [21,22,23].

5. Conclusions

Posture control is provided by numerous anatomical structures, a situation in which it can be influenced by various factors such as non-specific low back pain, which becomes more evident in situations with specified requirements.

Our results on directional indices and OR are consistent with the results in the literature and confirmed that to keep the body upright, the neuromuscular system must devote 50% more effort to control stability in the AP direction.

The average value of the DI on the two calculated directions, whose contribution relative to the displacement of the COP in the frontal and sagittal planes showed that 2/3 of the oscillations (approximately 60%) are in the AP direction. This proportion does not change even if the visual input is modified.

Our results also demonstrated gender differences in postural oscillation characteristics. In general, female subjects in the study appear to have a lower level of postural stability compared to male subjects. Therefore, the higher values of the OR observed in the female group indicate the need for intense muscle activity to maintain a stable posture in standing. In both groups, however, there were no differences in the values of the DI.

We consider it necessary to conduct additional research to determine the physiological changes that occur in the postural control system when changes in COP variables are detected. The characteristics of the COP are insufficient to address all aspects of assessing postural stability.

The study's findings hold clinical relevance in rehabilitation, fall prevention, sports performance, and elderly care. Clinicians can tailor rehabilitation programs to address gender-specific differences in postural control, enhancing balance and reducing fall risks. Effective fall prevention strategies can be developed by focusing on improving AP stability, especially in individuals with visual impairments. Assessments of balance disorders can be refined using the study's directional indices and OR, leading to more targeted interventions. In sports, coaches can optimize training regimens by incorporating exercises that improve anteroposterior stability, enhancing athletes' performance and reducing injury risks. Elderly care can benefit from interventions targeting anteroposterior control to improve balance and prevent falls among older adults. The study underscores the importance of gender and visual input in postural stability, offering valuable insights for clinical practice. These insights can inform the design of tailored interventions to enhance postural control and reduce fall risks across various populations. Overall, the study's clinical applications extend to diverse healthcare settings, contributing to improved patient outcomes and quality of life.

Institutional Review Board Statement: The study was approved by the Ethics Commission of the Interdisciplinary Research Center of the National University of Physical Education and Sport from Bucharest no.162/03 2022.

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