Poszerzone streszczenie w języku angielskim

Introduction

The ability to maintain balance is a key element of daily human functioning. It affects independence in performing everyday activities, mobility, and overall quality of life. Balance maintenance is a complex process involving the vestibular, visual, and proprioceptive systems. The vestibular system, located in the inner ear, comprises the semicircular canals, utricle, and saccule, which respond to head acceleration [1]. The visual system provides information about the surrounding environment, including light intensity, object positions within sight, and the location of visible body parts. The proprioceptive system supplies sensory data about the relative positions of body parts. Proprioceptor sensory endings respond to deformation, and several groups of proprioceptors play a crucial role in movement control. They are sensitive to physical variables such as joint position, muscle length, contraction speed, and muscle force. The integration of information from these systems is essential for maintaining balance. Disorders in any of these systems can lead to balance control difficulties and an increased risk of falls. Impaired balance may result from neurological diseases, aging, vestibular disorders, sensory disturbances in the feet due to diabetes, or musculoskeletal injuries [1,2]. Disrupted balance can lead to falls, which, by causing injuries, may further worsen health conditions [3]. Falls and related injuries are among the leading causes of hospitalization in older adults, often resulting in loss of mobility and independence [4]. Therefore, monitoring and improving balance, especially in the elderly and those with chronic illnesses, is crucial for enhancing quality of life and reducing fall risks.

Maintaining a stable posture is a dynamic process that requires constant control and adjustments of the center of mass to sustain balance during everyday activities. The process of balance maintenance involves mechanisms related to postural preparation (PA) and postural compensation in response to destabilizing stimuli. Postural preparation occurs just before a disturbance and aims to prevent or minimize the negative effects of balance loss. In contrast, compensatory adjustments are designed to restore balance immediately after the disturbance [5, 6, 7]. Postural control mechanisms can be categorized as early (early postural adjustment – EPA), which occur approximately 600–

400 ms before the disturbance, preparing the body for the anticipated imbalance; anticipatory (anticipatory postural adjustment – APA), occurring approximately 150 ms before to 50 ms after the disturbance, preparing to counter the imbalance; or compensatory (compensatory postural adjustment – CPA), occurring approximately 70–300 ms after the disturbance, restoring balance [8, 9, 10]. These mechanisms primarily manifest as changes in the activity of postural muscles [8], the displacement of individual body segments, and shifts in the center of mass (COM) or center of pressure (COP) [6]. Stimuli triggering PA can be divided into two types: the first related to voluntary movement initiation [11], and the second external, originating from the environment, often leading to destabilization [5]. Research suggests that an external stimulus can trigger APA if the subject is aware of when the disturbance will occur [8, 10]. In rehabilitation and therapy, understanding these mechanisms is critical for identifying specific deficits in a patient's balance control system [12, 13], reducing the risk of falls [4, 14], and monitoring rehabilitation progress [15].

Scientists use various methods to assess the ability to maintain balance, with the most employed approach involving the analysis of center of pressure (COP) displacements. Metrics describing the ability to maintain a stable posture, based on COP displacements, are most frequently analyzed in the time domain [16, 17] and the frequency domain [18, 19]. The most popular time-domain metrics include COP path length, average COP velocity, COP ellipse area, and COP movement ranges in the anterior-posterior (AP) and medio-lateral (ML) directions. Assessments may also involve determining the position of the center of mass (COM), tracking head movements, and measuring trunk acceleration values [20]. Less frequently used methods, as described in the literature, include wavelet transform analysis [21, 22, 23] and probabilistic analyses based on entropy [24].

Frequency domain analyses complement time-domain analyses by identifying cyclic components in the COP signal. These analyses can reveal subtle changes that may be difficult to detect using standard time-domain metrics. Frequency domain approaches are particularly valuable in developing new diagnostic methods, especially for assessing balance abilities under sensory conflict conditions, both in real-world environments and through virtual reality (VR) applications. VR technology has gained popularity in recent years due to technological advancements, making it more accessible. The use of 3D imagery enables the creation of environments and stimuli that are challenging to replicate in the real world. Additionally, the wide range of customizable scenarios allows the diagnostic and rehabilitation process to be tailored to individual patient cases and abilities. As a result, VR is increasingly being applied in rehabilitation and diagnostics, particularly for conditions related to impaired balance. Research in sensory conflict scenarios, where different senses receive conflicting information, is especially relevant in this context. In such cases, participants are exposed to stimuli that directly or indirectly destabilize their posture. For example, a study might involve a person standing on stable ground while VR technology creates the visual illusion of a moving environment (e.g., by displaying oscillating surroundings) [18, 25, 26, 27]. Analyzing the body's response to these visual disturbances can offer valuable diagnostic insights into balance control and adaptability in dynamically changing environments. Impaired adaptability may serve as an early indicator of neurological disorders, such as Parkinson's disease or vestibular dysfunction [28].

Currently used methods for assessing balance abilities, such as time-domain [16, 17] and frequency-domain analyses of COP displacements [18, 19], offer valuable insights into postural stability. Commonly analyzed time-domain parameters include COP velocity, COP ellipse area, and COP displacement ranges in the anterior-posterior (AP) and medio-lateral (ML) directions. Typically, an increase in these parameters is interpreted as indicative of balance control issues [33]. In contrast, frequency-domain analyses facilitate the examination of cyclic components within the signal, identifying dominant frequencies, which aids in assessing changes in balance strategies. This approach is especially useful when studying the effects of cyclic disturbances in virtual reality environments [21, 22, 23], broadening the scope of balance assessments beyond what time-domain analyses provide. The incorporation of advanced technologies, such as IMU sensors, electromyography, and virtual reality, can further enhance the evaluation of balance abilities and postural preparation [29, 30, 31, 32]. However, these technologies require analyses that allow for a comprehensive understanding and interpretation of the data within the measured signal. While the methods described above detect changes in the signal that suggest alterations in balance strategies, they focus on global signal analysis or the cyclic nature of observed phenomena, often overlooking rapid, non-cyclic changes. These non-cyclic changes can be critical for diagnosing and treating patients with neurological, orthopedic, or vestibular disorders. Consequently, there is a need for the continued development of research methods that complement current measurements and analyses, providing a more complete understanding and interpretation of changes in balance abilities that may result from the progression of various diseases.

Research objective

The recognized need for developing measurement methods and exploring novel approaches to data analysis, aimed at improving our understanding of human balance control mechanisms, has led to the formulation of the following research objectives:

- Develop a methodology for measuring human balance abilities that assesses changes in postural control strategies in response to both anticipated and unanticipated destabilizing stimuli.
- Determine the impact of virtual and real destabilizing stimuli on postural preparation as a diagnostic tool for evaluating human balance abilities.
- Analyze the practical application of methods for detecting momentary postural corrections to assess changes in postural control strategies in response to virtual and real destabilizing stimuli.

This doctoral dissertation summarizes the results of a series of studies published in scientific articles, focusing on the mechanisms of postural control and the ability to maintain balance in humans. The work encompasses both theoretical aspects of postural control, including the development of new methodologies for analyzing stabilographic data, and practical clinical applications.

Research methods utilizing virtual reality (VR) were developed to analyze postural preparation in response to balance-disturbing stimuli. Additionally, non-cyclical changes in the center of pressure (COP) were measured to assess shifts in balance strategies. The studies evolved from simpler experiments evaluating balance in virtual reality environments [A1], to more complex real-world destabilizing stimuli [A2], and to the development of novel data analysis methods aimed at complementing traditional balance assessment techniques [A3, A4, A5]. The final phase involved applying these methods in clinical practice with patients diagnosed with Parkinson's disease (PD) [A6]. In studies involving VR and a simulated fall down the stairs [A1], it was confirmed that visual destabilizing stimuli affected participants' balance differently. Frequency analysis, particularly of head movements, provided more precise information about participants' responses to visual disturbances, suggesting that additional analyses could help detect subtle changes. This led to further studies using more pronounced destabilizing stimuli, including real-world perturbations and the integration of electromyography (EMG) and full-body kinematic measurements, to expand the scope of analysis. The second phase of research [A2] involved real-world disturbances, such as shifting ground, to activate postural preparation mechanisms (anticipatory postural adjustments—APA, and early postural adjustments—EPA). The results showed that awareness of an impending stimulus influenced postural reactions, particularly in terms of increased lower limb muscle tension. Understanding how the nervous system prepares for and reacts to external stimuli is crucial for diagnosis and rehabilitation. This phase highlighted the necessity for more advanced data analysis techniques to enhance balance assessment interpretation. The next research phase [A3] focused on extending traditional balance assessment methods by applying techniques inspired by stock market trend analysis. The Trend Change Index (TCI) was introduced, which defines the number of trend changes based on signal intersections from the Moving Average Convergence Divergence (MACD) algorithm. MACD is represented by two lines: the MACD line and the signal line. Their intersections indicate trend changes in COP displacement, and the TCI coefficient counts the number of these changes during measurement [A3 – A5]. To further validate the COP trend change analysis method, subsequent studies examined participants' responses to virtual reality-generated disturbances [A4] and real-world perturbations with shifting ground [A5]. The analysis showed that the number of trend changes, as well as the time and distance between them, influenced postural stability and indicated shifts in balance strategies. These findings suggest that trend change analysis may be valuable for diagnosing and assessing individuals with neurodegenerative diseases. The final phase of the research involved evaluating the practical application of trend change analysis in assessing balance in individuals with Parkinson's disease (PD) [A6]. In PD, trend analysis proved effective in detecting differences between "on" and "off" states during dopaminergic treatment, revealing changes in postural stability that were not detectable with traditional methods. This suggests that trend analysis may be valuable for monitoring disease progression and diagnosing neurological disorders. Additionally, trend analysis in PD patients allows for more precise tracking of disease progression, which could be critical for optimizing treatment and rehabilitation strategies.

Analysis of center of pressure displacements and head movements triggered by a visual stimulus created using the virtual reality technology [A1]

Balance disorders can indicate neurological diseases or result from the aging process. Standard balance tests, such as COP displacement measurements, are often insufficient for detecting subtle balance disturbances. As a result, there is an increasing need for more advanced methods capable of identifying changes that remain undetected by traditional time-domain analyses. In this context, virtual reality (VR) technology is playing an increasingly significant role, enabling the simulation of various destabilizing conditions. Through VR, it is possible to introduce destabilizing visual stimuli while maintaining stable ground, placing the individual in a situation of sensory conflict. Studies have described balance assessments in VR environments, often exposing participants to moving surroundings or simulations of everyday situations. Analyzing reactions to these visual disturbances provides valuable insights into the mechanisms underlying postural stability. In balance assessment studies, time-domain parameters are typically analyzed. However, while time-domain values often increase under sensory conflict conditions, they do not always correlate directly with balance disorders, particularly those caused by neurological conditions. This underscores the need for new measurement and analysis methods capable of detecting changes that are not visible in standard time-domain analysis. Frequency-domain analysis and the use of accelerometers complement traditional analyses by providing additional information, such as the cyclicity of COP movements or the characteristics of individual body segment movements.

Consequently, the research objectives of the first article in this series were as follows:

- determine whether a visual stimulus, in the form of a simulated fall down the stairs, affects postural control,
- assess whether incorporating frequency-domain analysis can enhance the interpretation of balance ability compared to time-domain analysis,
- evaluate whether head movement measurements can complement COP measurements by providing additional insights into the effects of visual destabilizing stimuli on balance ability,

- investigate whether a visual warning signal preceding the destabilizing stimulus influences head movements and COP displacement.

To answer the questions, a series of studies was designed involving 10 participants (7 women and 3 men) with an average age of 25 years and an average BMI of 23 kg/m^2. All participants reported no significant lower limb injuries or balance issues. However, three individuals - one with severe motion sickness and a fear of heights (pp3), and two others (pp1, pp2) with elevated parameters indicating potential balance issues - were excluded from the healthy group, and separate analyses were conducted for each case. The study was conducted using the WinFDM-S measurement platform and the HTC Vive VR set. The VR application, developed in Unity 3D, presented a simple room scenario where the participant's avatar stood at the top of a staircase leading downward (Figure 1). Throughout the 60-second trials, both COP and head movements were recorded. Prior to the VR tests, participants underwent balance assessments on the platform in a real-world setting, with eyes open (EO) and eyes closed (EC). In the first test, a simulated fall down the stairs was triggered at the 30-second mark (BB). In the second test, participants received a visual warning signal 3 seconds before the simulation (BZ). Each test was repeated three times.

Figure 1 VR scenery [A1]

The analysis of the results was conducted in three stages. In the first stage, comparisons were made between the values of COP displacement velocity (V_{COP}), head movement velocity (V_{head}), and COP ellipse area (EA_{COP}) in both real and VR environments to assess the impact of destabilizing visual stimuli. The second stage involved analyzing the range of COP and head movements (DAD) in the anterior-posterior (AP) direction. The final stage consisted of a case study comparing the parameters of individuals with balance difficulties to those without such issues. Statistical analysis was performed using Statistica 13 software. Since none of the variables followed a normal distribution, non-parametric tests were used to compare differences.

To determine whether the simulated fall down the stairs could induce balance loss and whether COP displacements and head movements could identify balance-related issues, the analysis was conducted in two ways: first, by evaluating changes in parameters describing destabilization and postural compensation in a group of healthy individuals, and second, by comparing the results of those more susceptible to visual disturbances with the healthy group.

The analysis of parameters describing destabilization and postural compensation in the healthy group revealed that the destabilizing visual stimulus did not significantly affect participants' behavior. No significant differences were found between their reactions with and without the warning signal. It is likely that the visual stimulus (a simulated fall downstairs) was too unrealistic to elicit substantial changes, even when participants were aware of its occurrence and had experienced it before. Among the subjects, three individuals—one with severe motion sickness and a fear of heights, and two others with elevated balance parameters—stood out. Their differing results suggest potential balance difficulties under specific conditions, such as being at heights or experiencing unexpected ground movement. The study did not find significant differences in average COP or head movement velocities between healthy individuals and those more susceptible to disturbances, indicating that these parameters alone may be insufficient for detecting balance problems. More noticeable differences were observed in COP ellipse area and head movements, where the values for the three individuals were higher than the rest of the group, suggesting greater difficulty in maintaining balance after a disturbance. Frequency analysis revealed that the visual stimulus triggered a cyclic component with the highest amplitude between 0.1 Hz and 0.2 Hz in the COP AP signal. While no differences were found between tests with and without the warning signal, significant differences were observed between the three individuals and the rest of the participants, particularly in the first harmonic amplitude related to head movements. These results suggest that head movements dominated over COP displacements in their balance strategy, which could be key in diagnosing balance problems.

In summary, visual stimuli in VR affect individuals differently. Although the simulated fall down the stairs was designed to assess postural responses to a sudden visual disturbance, it did not significantly impact the postural control of most participants. This suggests that stronger or more realistic visual stimuli are needed to assess postural stability effectively. Frequency domain analysis, particularly the first harmonic amplitude of head movement signals, was better at distinguishing individuals susceptible to visual disturbances. While these findings do not necessarily indicate health issues, they may suggest increased susceptibility to unexpected stimuli requiring rapid head movements. To fully understand the mechanisms behind responses to external destabilizing stimuli, further analysis using electromyography (EMG) and expanded kinematic assessments of body movements - especially those of the lower limbs and knee joints - is necessary. The findings highlight the need for further refinement of methods simulating visual destabilizing stimuli and balance assessment techniques that detect changes not captured by standard time and frequency domain analyses.

The effect of selected lower limb muscle activities on a level of imbalance in reaction on anterior-posterior ground perturbation [A2]

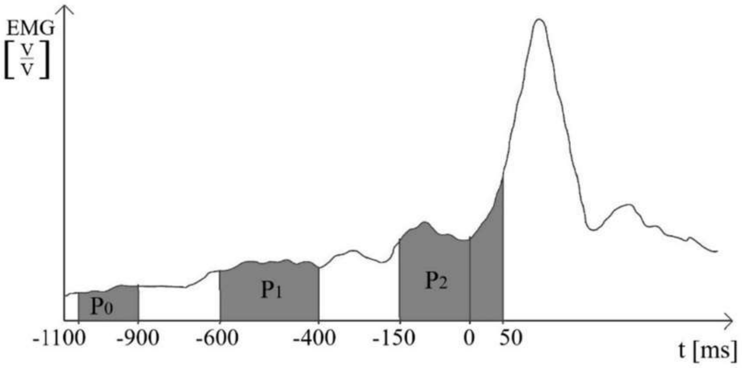
This article continues previous research on motor responses to visual disturbances, introducing a novel approach by applying real balance disruptions in the form of destabilizing ground shifts. Mechanisms of Anticipatory Postural Adjustment (APA) and Early Postural Adjustment (EPA) play a crucial role in adapting the body to external stimuli, helping to maintain balance and postural stability. In recent years, research on APA and EPA has become increasingly important, especially for diagnosing postural disorders and predicting falls. Observing these mechanisms provides deeper insights into how the body controls postural responses. Tools such as stabilographic platforms, electromyography systems, and IMU sensors offer more comprehensive and precise monitoring of muscle activity, COP displacements, and overall body kinematics. This article explores the practical applications of these mechanisms in assessing postural stability and their potential use in rehabilitation and injury prevention.

The aim of this study is to investigate whether knowledge of the timing of an actual balance-disrupting stimulus affects lower limb muscle tension before the disturbance occurs. Specific objectives include detecting the occurrence of APA and EPA, determining whether increased muscle activity is continuous over time or short-lived before the disturbance, and whether early muscle tension during the EPA phase leads to increased muscle tension in the APA phase. Additionally, the study aims to assess whether the increase in lower limb muscle tension before the disturbance results from postural changes that shift the center of mass forward or backward, increase or decrease forefoot pressure on the ground, or increase knee flexion angles.

To address the objectives, a series of studies was conducted involving 38 participants (27 women and 11 men) with an average age of 23 years, an average height of 172 cm, and an average weight of 70 kg. All participants reported no history of serious lower limb injuries, motor system dysfunctions, or balance disorders. The measurement setup consisted of a foot pressure measurement platform (WinFDM-S), a treadmill for postural perturbation training and assessment (BalanceTutor), which allowed for destabilizing displacements of the ground in both the anterior-posterior (AP) and medio-lateral (ML) directions, a wireless electromyography system (Ultium EMG), and IMU sensors (Ultium Motion). The stabilographic platform was centrally positioned on the treadmill and securely fixed in place. An IMU sensor was placed in a specially designed holder on the treadmill belt in front of the platform (Figure 2). All systems were synchronized using Noraxon MR3 software and an M5stack platform with an ESP32 microcontroller, enabling quick detection of treadmill movement.

Figure 2 Measurement stand [A2]

Based on the literature review, four muscles were selected for the electromyographic studies due to their key roles in maintaining balance: the tibialis anterior (TA), rectus femoris (RF), medial gastrocnemius (GM), and lateral gastrocnemius (GL). These muscles are commonly examined in studies investigating Anticipatory Postural Adjustments (APA) and Compensatory Postural Adjustments (CPA). Surface electrodes were placed on the skin near the muscle bellies and connected to wireless EMG sensors. Additionally, 17 IMU sensors, each containing an accelerometer, gyroscope, and magnetometer, were used to track joint angles. These sensors were placed on the torso, limbs, and head. The test procedure consisted of two stages: rest (ERx) and perturbation (Tr). During the rest stage, participants sat on a chair with their feet flat on the floor, relaxing their lower limb muscles for 15 seconds to record baseline muscle activity. In the perturbation stage, participants stood still on the stabilographic platform on the treadmill, facing forward with their arms relaxed at their sides, secured by a safety harness. The test consisted of three trials, each involving two treadmill movements—forward and backward. The first movement was always forward, initiated 10 seconds after the start of the measurement, while the backward movement occurred 20 seconds after the start. Both forward and backward displacements covered 9.5 cm and lasted 0.52 seconds. In the first trial (Tr1), participants were unaware of the nature, timing, or direction of the perturbation. In the second trial (Tr2), they knew the nature of the perturbation but not its timing or direction. In the third trial (Tr3), participants were informed of both the timing (with a countdown) and the direction of the perturbation. The following values were determined: t0 – the start of the movement, and EMGRx – the average muscle activity during the rest phase. To standardize the data, muscle activity in Tr1, Tr2, and Tr3 was divided by the EMGRx value. Next, muscle activity was analyzed in specific time intervals corresponding to different phases of muscle activation: free standing (P0), the period anticipating increased muscle activity due to EPA (P1), and the period of increased muscle activity caused by APA (P2) (Figure 3).



$$P_0 = \int_{-1100}^{-900} EMG\,dt,$$

$$P_1 = \int_{-600}^{-400} EMG\,dt,$$

$$P_2 = \int_{-150}^{50} EMG\,dt,$$

$$EMG_{EPA} = P_1 - P_0,$$

$$EMG_{EPA} = P_2 - P_0.$$

Figure 3 Time intervals and equations for determining muscle activity [A2]

EMGAPA and EMGEPA values were identified for each muscle assessed. These values were then correlated across all analyzed muscles during the Tr3 test. Additionally, forefoot pressure and knee flexion angle were calculated relative to the Tr3 test. The study then assessed whether increased muscle activity related to APA affected the displacement and velocity of the COP following balance loss. Statistical analysis was performed using Matlab R2022a, utilizing the Friedman ANOVA test and Wilcoxon's post-hoc test with Holm's correction. Due to the non-normal distribution of the data, Spearman's correlation was also calculated.

The results showed an increase in muscle tension only when participants were aware of the timing of the disturbance. The study aimed to define the strategy of postural preparation and its impact on postural compensation after the disturbance. Statistically significant differences in EMGAPA and EMGEPA between Tr1 and Tr3, as well as between Tr2 and Tr3, were observed only for forward movement in the TA, GL, and GM muscles during APA, and for TA and GM (only in the left leg) during EPA. Significant correlations between EPA and APA indicated that the TA and GM muscles were activated earlier, with activity increasing until the disturbance occurred. No significant differences were found in forefoot pressure or knee flexion angle across the Tr1, Tr2, and Tr3 tests. A correlation between increased muscle activity and both COP velocity and maximum displacement after the disturbance was noted, particularly for the TA muscle during forward movement and GL during backward movement. In both cases, increased muscle tension led to extended COP path length and velocity.

The study aimed to evaluate the effect of forward and backward ground displacement on lower limb muscle responses related to postural adaptation by examining muscle activity, knee flexion, and pressure on the ground in relation to COP displacement. APA and EPA phenomena were identified based on muscle activity, and the analysis revealed an increase in average muscle activity during APA in Tr3, when participants were informed of the disturbance's timing. The TA muscle was shown to play a crucial role in adapting to postural disturbances. Due to the lack of significant differences in knee flexion, COP displacement, and forefoot pressure between Tr1, Tr2, and Tr3, it can be inferred that postural adaptation to the disturbance was not associated with forward or backward trunk leaning, and the observed increase in TA, GL, and GM muscle tension did not affect knee flexion. The strong correlation between muscle tension and COP displacement and velocity after the disturbance, especially between TA tension and COP behavior, suggests that increased muscle tension during the APA phase contributed to joint locking before the disturbance, thereby altering postural compensation and increasing both COP path length and velocity.

The study clearly confirmed that the key factor triggering postural adjustment and readiness for disturbance was awareness of the anticipated timing of the perturbation. Muscle tension, which stiffened the lower limb joints, was crucial for preparing for the disturbance, leading to greater COP displacement after the disturbance. Combining real-world disturbances, such as unexpected and anticipated ground shifts, with EMG and

IMU analysis offers a precise assessment of balance control mechanisms. This approach provides new insights into the interaction between the nervous and muscular systems in maintaining balance, which is especially important for fall prevention and rehabilitation. The results emphasize the need for broader analysis of postural responses to real destabilizing stimuli, such as ground displacement. The introduction of a new analytical methodology capable of detecting non-cyclical changes, which standard analyses often miss, could be highly beneficial. Understanding how the body prepares for and responds to external balance disturbances is key to developing improved diagnostic and rehabilitation methods that can more effectively enhance postural stability and reduce the risk of falls in everyday situations.

The stock market indexes in research on human balance [A3]

Previous studies on balance maintenance ability have primarily focused on measuring center of pressure (COP) displacements, including parameters like COP velocity, ellipse area, and displacement range in different directions. When balance-disturbing stimuli are cyclical, frequency-domain analyses can provide valuable insights into the body's response. However, frequency analysis is limited to detecting cyclical changes in COP positions and may overlook non-cyclical changes that are also critical for assessing balance maintenance strategies. In this context, new analytical methods inspired by stock market price trend analysis techniques can expand traditional approaches by incorporating momentary, non-cyclical changes in COP and center of mass (COM) movements. These advanced approaches can not only enhance diagnostic accuracy but also allow for earlier detection of balance disturbances, which is particularly important for fall prevention and reducing injury risks. The third article in this series introduces a balance analysis method based on a stock market index, aiming to complement both time-domain and frequency-domain analyses in virtual reality studies [A1] and postural preparation and compensation analyses [A2].

This article explores the use of the Moving Average Convergence/Divergence (MACD) index - typically associated with stock price trend analysis - to evaluate balance maintenance ability in both real-world and virtual reality environments. The study aimed to demonstrate the feasibility of applying stock market indicators to assess balance ability, complementing traditional time and frequency-domain analyses. By detecting significant trend changes - directional shifts - in COP movement and identifying the time intervals between successive changes, this analysis could capture both cyclical and non-cyclical components within a specific frequency range.

The study involved 83 healthy participants (56 women and 27 men) with an average age of 21 years, an average height of 172 cm, and an average weight of 65 kg. All participants reported no history of significant lower limb injuries, motor system dysfunction, or balance disorders. The study was conducted using the WinFDM-S measurement platform and the Oculus Rift VR system. The VR application, developed in Unity 3D, presented two scenarios: an "open" desert scene with objects visible at approximately 100 meters, and a "closed" room scene with furniture and objects at about 3 meters. During the measurements, the scenes oscillated in the sagittal plane at fixed frequencies. The testing procedure included measurements taken in both real-world environments (with eyes open and closed) and in virtual environments using the two oscillating scenes ("open" and "closed") at different frequencies (0.2 Hz, 0.5 Hz, 0.7 Hz, and 1.4 Hz). Participants stood barefoot on the measurement platform with their arms crossed over their chest and heads facing forward. The measurements focused on COP displacements during 30-second tests. Data analysis was conducted using MATLAB software. In the first stage, the average COP velocity, and the range of COP movement in the AP direction were analyzed. This was followed by a frequency analysis to determine the Power Spectral Density (PSD) of COP displacement in the AP direction. Additionally, the Trend Change Index (TCI) was calculated to define the number of trend changes based on the Moving Average Convergence Divergence (MACD) index.

The MACD index is represented by two lines: the MACD line and the signal line. The MACD line was obtained by subtracting the slow-moving average (26-period average) from the fast-moving average (12-period average) (Equation 1, Equation 2).

Equation 4

$$MACD_{12,26} = EMA_{12} - EMA_{26}$$

where:

EMA_{12} – faster exponential moving average,

EMA_{26} – slower exponential moving average;

Equation 2

$$EMA_{pN} = \frac{p_0 + (1-\alpha)p_1 + (1-\alpha)^2 p_2 + (1-\alpha)^3 p_3 + \cdots + (1-\alpha)^N p_N}{1 + (1-\alpha) + (1-\alpha)^2 + (1-\alpha)^3 + \cdots + (1-\alpha)^N}$$

where:

p0 – ultimate value,

pN – value preceding N periods,

N – number of periods.

The signal line was obtained by calculating the moving average with exponential weight for the MACD signal considering the nine MACD signal samples (Equation 3).

Equation 3

$$Signal\ Line = EMA_{MACD,9}$$

The intersection of the MACD line and the signal line indicates a trend change in the COP displacement signal in the AP direction. These trend changes correspond to shifts in the direction of COP movement. The Trend Change Index (TCI) coefficient defines the number of trend changes in the signal during a 30-second test and is calculated as the total number of intersections between the MACD and signal lines.

The calculated PSD and TCI values were used to analyze the participants' responses to disturbances. The effects of different virtual scenarios and oscillation frequencies were compared, as well as the differences between the virtual and real-world environments. Calculations for both PSD and TCI were focused on the AP direction. A detailed analysis revealed that the time intervals between individual trend changes varied. As a result, these detected trend changes were grouped based on the time intervals preceding them. These time intervals were then converted into corresponding frequencies, enabling a comparative analysis between the MACD and PSD coefficients (Table 1).

Table 1 The time intervals considered during the analyzes [A3]

T [s]	0.05–0.1	0.1–0.2	0.2 – 0.3	0.3 – 0.4	0.4 – 0.5	0.5 – 0.6
f [Hz]	5.0-10.0	2,5-5.0	1,67-2,5	1,25-1,67	1.0-1,25	0,83-1.0
T [s]	0.6 – 0.7	0.7 – 0.8	0.8 – 0.9	0.9 – 1.0	0.05-1.0	1.0-30.0
f [Hz]	0,71-1.0	0,625-1	0,56-0,625	0,5-0,56	>0.5	<0.5

The statistical analysis of the results was conducted using Statistica 13 software. A Kruskal-Wallis ANOVA test and Dunn's post-hoc tests were performed to determine whether statistically significant differences existed among the analyzed groups.

The measured values of subsequent COP positions over time were processed using time, frequency domain analyses, and trend analysis. In the time-domain analysis (average COP velocity, average COP velocity in the AP direction, range of movement in the AP direction), a statistically significant increase in measured values in the virtual environment was observed compared to the real environment for most measurements. However, there were no significant differences for average COP velocity and range of movement in the AP direction at oscillation frequencies of 0.2 Hz and 0.5 Hz. PSD and TCI coefficients were calculated for the AP direction. The PSD analysis showed statistically significant differences when comparing tests with open eyes (EO) to all other measurements, as well as within the 0.5–10 Hz range for tests with closed eyes (EC) compared to the "open" and "closed" VR scenes at oscillation frequencies of 0.5 Hz, 0.7 Hz, and 1.4 Hz. No significant differences were found between the virtual environment tests themselves for both PSD and TCI values. Comparisons of PSD and TCI values indicated that the maximum values were obtained at oscillation frequencies of 0.7 Hz and 1.4 Hz, regardless of the scene type. Statistically significant differences were also observed when comparing the virtual environment tests at frequencies of 0.2 Hz and 0.5 Hz with those at 1.4 Hz.

Traditional metrics used to describe balance ability, such as COP path length, average velocity, and movement range, tend to increase in healthy individuals when standing on unstable surfaces or in situations of sensory conflict. In such cases, frequency analysis allows for the decomposition of the COP movement signal into cyclic components and identification of dominant movement frequencies. However, traditional methods often fail to detect non-cyclic corrections in COP position. The proposed analysis method using stock market indices enabled the detection of both cyclic and non-cyclic trend changes in COP movement. A new coefficient, the Trend Change Index (TCI), was introduced to define the number of trend changes in the COP displacement signal. The analysis of trend changes across different measurements showed that the number of these changes remained consistent across tested conditions. This suggests that balance control requires a certain number of rapid trend changes in COP movement (within time intervals of 0.05–1.0 s, corresponding to frequencies of 10 Hz to 0.5 Hz). Destabilizing conditions, such as the introduction of an oscillating visual scene, did not significantly alter this number. From this, it can be inferred that either the balance system does not require additional movements, or the motor system is unable to generate them.

The presented results show that traditional methods of analysis, such as measuring COP path length, average velocity, and movement range, are effective in assessing general balance ability but may not fully capture subtle, non-cyclic changes in COP displacement. The proposed trend analysis method, based on a stock market index, allows for the detection of rapid, non-cyclic postural corrections, which could provide new diagnostic insights, especially for individuals with balance disorders. Further development and testing of this method are necessary under a variety of stimuli, both in virtual reality environments and in real-world simulations that mimic everyday scenarios. It is especially important to assess this method on individuals with neurodegenerative diseases, where subtle changes in balance may be critical for early diagnosis and monitoring disease progression. Integrating this method into clinical practice could lead to more precise balance assessments and a better understanding of proprioceptive control mechanisms.

Impact of Visual Disturbances on the Trend Changes of COP Displacement Courses Using Stock Exchange Indices [A4]

The fourth article in the series builds on previous research introducing trend analysis in balance assessment [A3], while addressing the need for further development of this method to enhance the analysis of measurement results in a VR environment with disturbances. The article aimed to determine whether trend change analysis (TCI) can effectively complement standard balance assessment methods by identifying the number of postural corrections (TCI) and introducing additional indicators based on TCI. Furthermore, the study sought to determine whether a reduction in the frequency of postural corrections and an increase in the distance between trend change points could serve as indicators of increased fall risk, which could be applied in balance diagnostics and evaluation.

The study involved 28 healthy participants (13 women and 15 men) with an average age of 22 years, an average height of 173 cm, and an average weight of 68 kg. Exclusion criteria included health problems related to balance or the vestibular system, as well as obesity (body mass index BMI > 30). The experiment was conducted using the WinFDM-S measurement platform and the Oculus Rift VR system. The 3D scenes were developed in the Unity 3D environment. The "closed" scene depicted a furnished room with objects visible to the participant at approximately 3 meters, while the "open" scene portrayed a desert landscape with objects located about 100 meters away. During the tests, the scenes oscillated in the AP direction at a constant frequency. The experimental procedure included tests in a real-world environment, where participants stood with eyes open (EO) and eyes closed (EC), as well as tests conducted in the virtual environment.

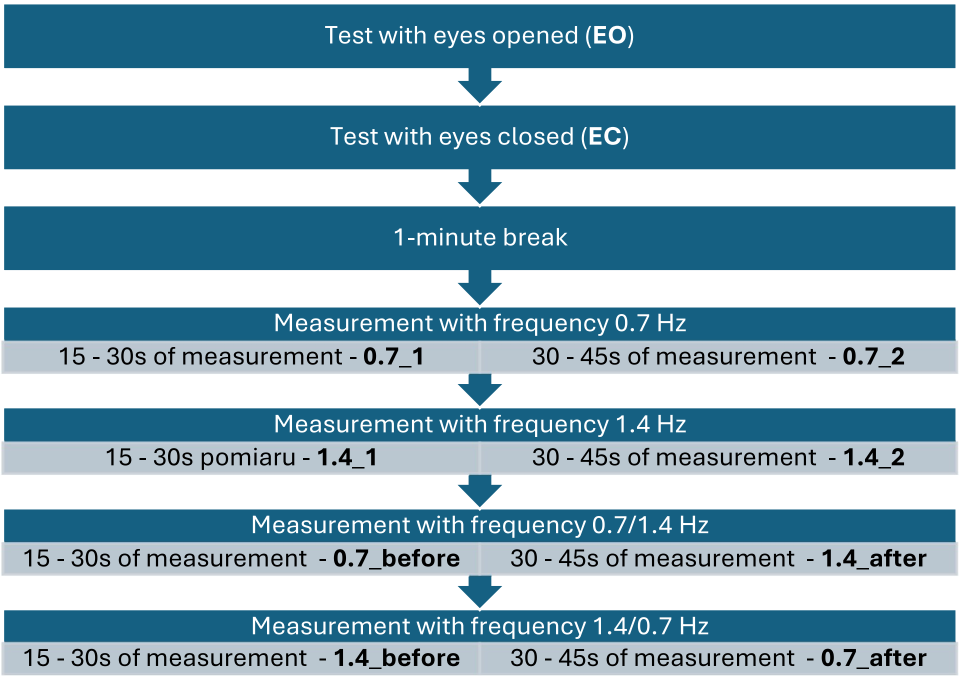


Figure 4 Experimental procedure [A4]

Measurements in VR were conducted using both open and closed scenes oscillating at frequencies of 0.7 Hz and 1.4 Hz, as well as with frequency changes midway through the test—from 0.7 Hz to 1.4 Hz and from 1.4 Hz to 0.7 Hz (Figure 4). Participants stood barefoot on the measurement platform, with arms crossed over their chest and head facing forward. Each measurement lasted 60 seconds, and the analysis focused on the period between the 15th and 45th seconds, during which oscillations occurred in tests with the oscillating scenes.

The measurement data were processed using MATLAB software. The analysis focused on COP displacements in the AP direction during EO and EC tests, as well as during the middle 30 seconds of tests with scene oscillations at 0.7 Hz and 1.4 Hz, including the 15 seconds before and 15 seconds after the frequency changes. Basic stabilographic parameters, such as COP velocity and COP displacement range in the AP direction, were calculated, along with the Trend Change Index (TCI). The TCI was expressed as both the total number of trend changes for the entire measurement and the number of trend changes within specific time intervals: 0–0.2 s, 0.2–0.5 s, and 0.5–1 s. Each time interval represents the time elapsed between consecutive trend changes. Additionally, the following values were calculated based on the TCI algorithm: the average distance between consecutive trend change points (MACD_dS), the average time between consecutive trend change points (MACD_dT), and the average velocity of displacements between consecutive trend change points (MACD_dV).

For the statistical analysis, due to the non-normal distribution of the data, Friedman's ANOVA and Wilcoxon post hoc tests with Holm correction were applied. The analysis divided the results into three groups: standard time-domain values, TCI values for the entire measurement, and values calculated based on trend analysis (MACD_dT, MACD_dS, MACD_dV). COP velocity in the AP direction significantly increased after participants closed their eyes and when visual disturbances were introduced in VR. However, no statistically significant differences were found for TCI values between EO and EC. Statistically significant differences in TCI values were observed when comparing the EO test in the real environment with measurements in the virtual environment using the 0.7 Hz oscillating scene. Introducing VR disturbances decreased the median TCI values in the 0–0.2 s time interval. For the 0.2–0.5 s interval, higher median values were observed in the 1.4 Hz oscillating scene tests, while the highest values for the 0.5–1 s interval were observed in VR tests with 0.7 Hz disturbances. In terms of MACD_dS values, a significant increase was noted in VR tests compared to real-world measurements, but no significant differences were found between VR tests. For MACD_dT, significantly higher values were observed in measurements conducted at a 0.7 Hz frequency. Median MACD_dV values increased after participants closed their eyes and when virtual reality was introduced.

The results show that in most cases, the TCI value remained consistent across different testing conditions, suggesting that maintaining balance requires a certain number of postural corrections. The MACD_dS, MACD_dT, and MACD_dV values provided additional insights into COP movement, indicating whether changes in velocity result from shifts in COP distance, time taken, or both factors. The study also found that the MACD_dT value, which did not significantly decrease, plays a critical role in maintaining balance. The simultaneous increase in MACD_dS and decrease in MACD_dT—indicating longer COP jumps in shorter times—could lead to destabilization and potential falls.

Using stock market indicators to assess human stability complements standard time- and frequency-domain analyses. Analyzing TCI, MACD_dV, MACD_dT, and MACD_dS values offer new insights into factors affecting traditional balance parameters, such as path length, average velocity, and movement range. By integrating trend change analysis with stabilographic measurements, we can gain valuable information about the frequency of postural corrections, the intervals between corrections, and the speed of COP movement.

Trend change analysis in the assessment of body balance during posture adjustment in reaction to anterior-posterior ground perturbation [A5]

The fifth article in this series combines research on postural responses to external destabilizing stimuli [A2] with the innovative Trend Change Analysis (TCA) method for assessing balance [A3, A4]. Traditional methods of postural analysis, such as muscle activity measurements and center of pressure (COP) displacements, can be complemented by TCA. Inspired by stock market analysis techniques, TCA enables the identification of rapid postural corrections and the analysis of non-cyclical changes in the COP signal, providing new insights into balance maintenance strategies and responses to destabilizing stimuli. The article also highlights the need for further development and testing of TCA in real-world environments with actual balance-disturbing stimuli. This article hypothesizes that an increase in COP velocity may result from a shift in balance maintenance strategies, which should be reflected in trend analysis parameters, such as the number of trend changes and the time and distance between them. The aim of the study was to determine whether different conditions during the examination of postural preparation phenomena affect the values obtained through trend analysis.

The study involved 38 participants (27 women, 11 men), with an average age of 23 years, an average height of 172 cm, and an average weight of 70 kg. Exclusion criteria included previous lower limb injuries and balance issues. The testing setup consisted of a foot pressure measurement platform (WinFDM-S) and a treadmill (BalanceTutor) for postural perturbation training and assessment, which allowed for destabilizing ground displacements in the anterior-posterior (AP) and medio-lateral (ML) directions. A wireless electromyography system (Ultium EMG) and IMU sensors (Ultium Motion) were also used. The stabilographic platform was securely attached to the treadmill, and electrodes and EMG system sensors were placed near the muscle bellies of the tibialis anterior (TA), rectus femoris (RF), and the medial and lateral heads of the gastrocnemius (GM)—muscles actively involved in maintaining balance in the AP direction. An IMU sensor was attached to the treadmill belt, enabling detection of the onset of perturbations caused by platform movement and synchronization of all devices (Figure 5). The testing procedure involved three trials. In the first trial (Tr1), participants were unaware of the timing or direction of the perturbation. In the second trial (Tr2), participants knew the perturbation would occur but were unaware of its exact timing or direction. In the third trial (Tr3), participants were informed of the exact timing and direction of the perturbation, with a countdown displayed on a screen. In each trial, the platform made two movements - one forward and one backward - each 9.5 cm long and lasting 0.5 seconds.

Figure 5 Measurement stand [A5]

After the measurements were completed, both time-domain values and trend change analyses were conducted. The analysis included the calculation of the average COP velocity and several trend change characteristics: the total number of trend changes during the entire test (TCI), the average distance between consecutive trend change points (TCI_dS), the average time between consecutive trend change points (TCI_dT), and the average velocity of instantaneous displacements between consecutive trend changes (TCI_dV). The Shapiro-Wilk test revealed non-normal distributions for all variables, so statistical analysis was conducted using medians and non-parametric tests. The results from Tr1, Tr2, and Tr3 were compared using the Friedman test and Wilcoxon pair tests with Holm correction.

The EMG signal analysis showed differences in lower limb muscle activation across the trials, particularly in Tr3, where earlier preparation for the balance disturbance (EPA and APA) was observed [A2]. The studies confirmed that varying levels of muscle activation influenced COP signal characteristics, as reflected in changes to parameters such as TCI_dS and TCI_dV. Notably, in Tr3, a significant increase in the distance between consecutive trend change points was observed one second before the disturbance, suggesting a shift in balance strategy. This increase was also evident in the number of COP displacements within specific time intervals. When participants were aware of the impending disturbance, COP velocity (V_{COP}) increased, indicating a potential shift in balance strategy. Despite the increase in V_{COP}, the number of trend changes (TCI) remained constant, suggesting that these changes were due to longer distances covered by COP rather than more frequent postural adjustments. It was also observed that increased muscle tension, caused by the anticipation of the upcoming movement, led to body stiffening, which may have altered balance maintenance characteristics. These studies suggest that the body's responses to balance disturbances are complex and vary depending on the participant's awareness of the disturbance.

The trend change analysis method complements traditional COP analyses and EMG measurements in studies of postural preparation. TCI-based metrics help explain phenomena such as increased COP velocity, providing insights into the mechanisms underlying balance maintenance strategies.

Trend change analysis of postural balance in Parkinson's disease discriminates between medication state [A6]

The sixth article in the series describes the use of an innovative trend analysis method in balance studies utilizing IMU sensors in a group of individuals with Parkinson's disease (PD). These studies have the potential to significantly impact clinical practice by providing more precise tools for monitoring disease progression and developing new diagnostic methods through detailed postural stability analyses. The article was produced in collaboration with the University of Kiel, where the measurements were conducted.

The research presented in the article had two primary objectives: to investigate the potential application of trend change analysis (TCA) for assessing postural stability using IMU sensors and to apply this analysis in the context of neurological diseases, particularly PD. The hypothesis was that TCA could distinguish between individuals with Parkinson's disease (pwPD) and healthy adults, as well as differentiate between the "on" (PDon) and "off" (PDoff) phases associated with taking dopaminergic medications.

The study group consisted of 61 healthy individuals, divided into two subgroups: young adults (YO) comprising 40 participants with an average age of 30 years, an average height of 185 cm, and an average weight of 80 kg; and older adults (OP), comprising 21 participants with an average age of 73 years, an average height of 181 cm, and an average weight of 84 kg. Additionally, 29 individuals with Parkinson's disease (pwPD) participated in the study. Among the Parkinson's subgroup, 13 individuals were assessed as PDoff (UPDRS III score of 24 ± 10), 23 as PDon (UPDRS III score of 30 ± 20), and 7 were evaluated in both PDon (UPDRS III score of 26 ± 10) and PDoff (UPDRS III score of 27 ± 10) conditions. All participants with Parkinson's were inpatients at the neurogeriatric ward of the Neurology Center at University Hospital Schleswig-Holstein in Kiel.

Three IMU sensors (Ultium Motion) were attached to participants' bodies—on the pelvis, sternum, and head—using flexible straps (Figure 6). Participants were instructed to stand upright with their feet together and focus on a point on a white wall for 10 seconds as part of the Short Physical Performance Battery test.

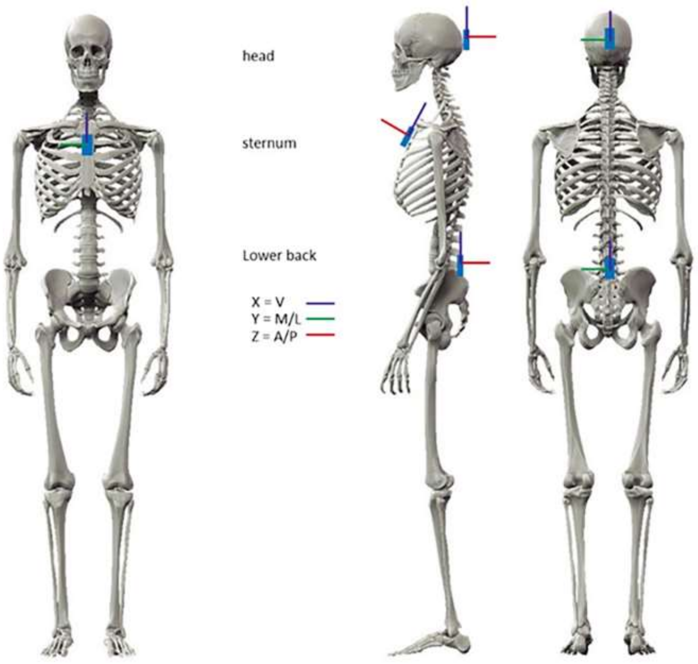


Figure 6 IMU sensors placement [A6]

Data from the IMU sensors were processed using MATLAB software. The following parameters were determined for center of mass (COM) movements: the sway jerkiness (JERK) (cm^2/s^5), the sway area (SURFACE) (cm^2), path (PATH) (cm), mean velocity (MV) (cm/s), acceleration range (RANGE) (cm/s^2), and root mean square of the acceleration (RMS) (cm/s^2). Additionally, trend change analysis (TCA) [A3, A4] was performed on the acceleration signal, yielding values for TCI (Trend Change Index), TCI_dT (average time between trend changes), TCI_dS (average distance between trend changes), and TCI_dV (average velocity between trend changes). Statistical analysis was conducted using MATLAB R2022a and JASP software. The Shapiro-Wilk test revealed non-normal distributions for all parameters, so non-parametric tests were applied. Differences between groups and sensor positions were analyzed using the Kruskal-Wallis test and post-hoc Dunn's test with Bonferroni correction.

The results confirmed that differences in movements between body segments can be detected using both traditional balance parameters and TCA. However, only TCA was able to distinguish between "on" and "off" states in individuals with PD. The findings suggest that during simple balance tasks, individuals with PD may exhibit behavior similar to healthy individuals, due to compensatory mechanisms in the central nervous system. The study showed that dopaminergic treatment influences postural stability. TCA results indicated a higher number of trend changes (TCI) and lower TCI_dT values in the "off" state compared to the "on" state, potentially reflecting visual and motor deficits caused by dopamine depletion.

The most significant conclusion from the study is that the introduction of trend change analysis (TCA) was crucial in detecting meaningful differences between the "on" and "off" treatment states in PD. This highlights TCA's potential for assessing disease-related changes that are not captured by conventional balance parameters.

Summary

The doctoral dissertation presents the results of research published in several scientific articles, focusing on the mechanisms of postural control and the ability to maintain human balance under various experimental conditions, including both real-world and virtual environments. The findings revealed that standard metrics, such as COP velocity - commonly used to assess balance - are insufficient to fully capture an individual's response to applied stimuli. Frequency analysis of head movements proved valuable, enabling the identification of individuals most susceptible to visual disturbances.

In studies examining the effect of real-world destabilizing stimuli on postural preparation phenomena, it was shown that knowledge of the timing of an impending disturbance was the key factor in triggering postural preparation and readiness. Additionally, the integration of stabilographic analysis, EMG, and IMU sensors provided a more precise assessment of balance maintenance mechanisms. The research confirmed that trend analysis, based on techniques from technical analysis, enhances traditional time and frequency domain analyses. The introduction of non-cyclic COP movement analysis allowed for a deeper evaluation of changes in balance strategy. This method proved applicable in both virtual reality studies involving oscillating disturbances and real-world scenarios with actual destabilizing stimuli.

The development of these analytical methods opens new opportunities for diagnosing balance disorders, particularly in relation to neurodegenerative diseases such as Parkinson's disease. The application of these tools in clinical practice enables the early detection of postural stability changes that may not be captured through traditional balance assessment methods.

In conclusion, the conducted studies successfully achieved the research objectives. The use of destabilizing stimuli, both real and virtual, significantly broadens the scope for analyzing balance capacity. The incorporation of methods that detect momentary postural adjustments, such as trend analysis of COP signals, enhances the ability to interpret phenomena associated with body destabilization. This approach allows for

more precise monitoring of postural stability, which is crucial for rehabilitation, fall prevention, and the diagnosis of neurodegenerative diseases.