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The stock market indexes in research on human balance

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Purpose: The aim of the study was to demonstrate the possibility of using stock exchange indices to assess the ability to maintain balance as a supplement to analyzes using values determined in the time and frequency domains. *Methods*: 83 healthy people (56 females, 27 males, age years 21 SD = 1.3 years) participated in the research. Measurements were performed with open and closed eyes and in the virtual environment with two sceneries oscillating at four frequencies. The results determined in the time and frequency domains were analyzed in relation to the results calculated with the use of stock exchange indicators for which the Trend Change Index was formulated. Performed measurements made it possible to determine the average COP speed, the average COP speed and range of movement towards AP, power spectral density PSD and stock exchange indices. *Results*: In the case of PSD values for the ranges above and below 0.5 Hz, statistically significant differences occurred for most measurements. Obtained values of TCI coefficient were similar and no statistically significant differences were observed. The maximum values of the PSD medians were obtained in trials with the oscillating scenery. *Conclusions*: Conducted analyzes showed that use of stock exchange indicators broadens the interpretative possibilities of COP measurements by determining the number of consecutive skips (changes in the direction) of the COP and prioritizing according to the times between them. The applied stock market analysis methods also filtered out changes in the position resulting from noises that could not be removed with the use of standard low-pass filters.

Key words: *postural stability, virtual reality, center of pressure, stock market indicators*

1. Introduction

Keeping the body in a standing position requires constant control and correction of the position, velocity and acceleration of the body's center of mass (COM) [9], [10]. Searching for the information about the strategies and mechanisms describing the process of maintaining balance has resulted in numerous approaches to analyzing center of pressure of foot on the ground (COP) changes – a value which is easy to measure and interpret. The most frequently used methods define these changes in relation to time [1], [6], [24], e.g., path length, the average COP velocity ellipse area or ranges in anteroposterior (AP) and mediolateral (ML) directions. As standard, it is assumed that the higher the value of the aforementioned quantities, the worse the ability to maintain balance [3], [4], [11]. Since some repetitive sequences can be seen in the COP displacement signal course, frequency domain analyzes are a natural extension of time domain analyzes. They make it possible to determine which cyclic components the analyzed signal consists of, thus complementing analyzes in the time domain [7], [13], [23]. Research in the virtual environment can be mentioned as an example of measurements in sensory conflict conditions where the oscillating virtual scenery was used with the still, real floor. Such cyclic movement of the surroundings causes changes in the body movement pattern, what changes COP motion. Then, for example, the increase in path length of COP can be explained by means of frequency

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analysis – one can check what cyclic components are part of the movement and whether the following scenery is a dominant one [12], [21]. Other methods, such as wavelet analysis [8], [17], [22] or entropy determination [5], [16], are used much less often.

However, frequency domain analysis is limited to changes that are cyclical in nature and only such changes in COP positions are detected. However, changes that are not of this nature are ignored. The ability to detect these types of changes – not cyclical – seems to be particularly important in terms of assessing the balance maintaining strategy. As proven, there is a relation between the frequency of COP movements and the strategy of maintaining balance, where low frequencies (0–0.5 Hz) mostly account for visuo-vestibular regulation, medium frequencies (0.5–2 Hz) for cerebellar regulation and high frequencies (>2 Hz) for proprioceptive regulation [2], [15]. However, speaking of frequency, it should be remembered that, in the case of successive COP positions, it should be interpreted as the rate of these changes, i.e., the time between individual changes in the COP position [20], [25]. With such an interpretation, it can be seen that determining the actual number of consecutive changes in the position of the COP, and not only those of a cyclical nature, becomes crucial [14], [19]. Moreover, the applied method should eliminate changes in the position that are too small – of a short time, which may constitute noises, and which remain in the signal even after the application of low-pass filters.

The aim of the study was to demonstrate the possibility of using stock exchange indices to assess the ability to maintain balance as a supplement to analyzes with the use of values determined in the time and frequency domains. The use of stock exchange indicators is to allow the detection of significant changes in the trend – changes in direction – in the COP movement along with the determination of the duration between consecutive jumps. Such an analysis should enable us, for a certain frequency range, to detect both cyclical components and non-cyclical changes

2. Materials and methods

Participants

The participants consisted of 83 healthy people (56 females and 27 males) with an average age of 21 years (SD = 1.3 years), mean body mass of 65 kg (SD = 12.2 kg) and an average height of 172 cm (SD = 8.3 cm). Health problems relating to maintaining balance and obesity (body mass index; BMI > 30) were considered as exclusion criteria. This study was first approved by the Ethics in Research Committee of the Academy of Physical Education in Katowice (protocol number 5/2020). In accordance with the Ethics in Research Committee, each participant provided informed consent regarding their participation in the study. Consent to participate in the study was expressed verbally (written consent was not required).

Measurement stand

Measuring equipment consisted of a platform for measuring the distribution of pressure exerted by the foot on the ground (WinFDM-S, Zebris, sample frequency of 100 Hz, 2560 tensiometer sensors, sensing area = 34 cm × 54 cm) and an Oculus Rift Head Mounted Display (HMD) for projecting spatial images. The virtual sceneries, which were projected during testing, were prepared in the Unity 3D environment. Two sceneries were prepared: the first scenery was termed “closed” (Fig. 1a) and consisted of a furnished room in which objects and the wall were seen by the participant at a distance of approximately 3 m; the second scenery was termed “open” (Fig. 1b) and consisted of a desert scene with objects seen at a distance of approximately 100 m.

Fig. 1a. View of closed scenery

Fig. 1b. View of open scenery

During measurements, the sceneries oscillated in the sagittal plane at constant frequencies. Participants saw the movement as movement of the entirety of the surroundings. The movement of the scenery was achieved by overlapping the following two movements:

- movement along the sagittal axis (AP direction) of the currently tested participant (Eq. (1))

$$y = A_y * \sin(2\pi f_t t), \quad (1)$$

where:

f_t – frequency of the scenery movements,

A_y – amplitude of the scenery movements in centimeters,

t – time;

- movement around the transverse axis of a given test participant (Eq. (2))

$$\phi = A_\phi * \sin(2\pi f_r t), \quad (2)$$

where:

f_r – frequency of the scenery movements,

A_φ – amplitude of the scenery movements in degrees,

t – time.

The following designations were adopted for the purpose of the tests utilized:

- $A_y = 15$ [cm],
- $A_\varphi = 1$ [deg],
- $f_r = 0.5 * f_t$,
- f_t (depending on test condition) = 0.2 Hz or 0.5 Hz or 0.7 Hz or 1.4 Hz.

Each test lasted 30 s. There was one trial for each condition of the measurement.

Experimental procedure

The procedure consisted of tests performed in the real and virtual environments. In the real environment, measurements were performed with eyes open (EO) and eyes closed (EC). Measurements in the virtual environment were performed using two sceneries ("open" and "closed") that oscillated with constant frequencies of 0.2 Hz, 0.5 Hz, 0.7 Hz and 1.4 Hz. Participants were required to take off their shoes and step on the measuring platform in an upright position. During measurements participants had to stand still with their arms crossed over their chests and their eyes focused on a designated point. Measurements were performed in the real environment followed by measurements in the virtual environment (Fig. 2). Participants were divided into four groups:

- "open" scenery at frequencies of 0.2 Hz (0.2 O) and 0.5 Hz (0.5 O),
- "open" scenery at frequencies of 0.7 Hz (0.7 O) and 1.4 Hz (1.4 O),
- "closed" scenery at frequencies of 0.2 Hz (0.2 C) and 0.5 Hz (0.5 C),
- "closed" scenery at frequencies of 0.7 Hz (0.7 C) and 1.4 Hz (1.4 C).

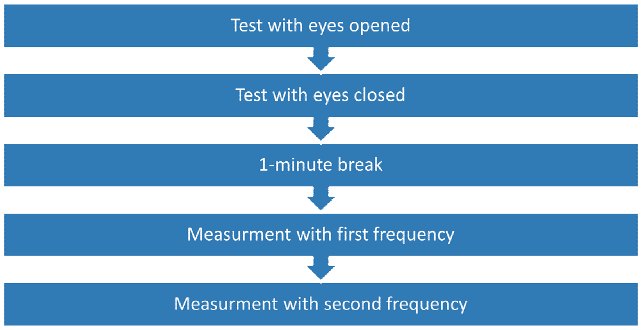


Fig. 2. Sequence of one measuring series

Each participant was tested in the real environment and then in a virtual reality environment:

- for a group of 40 participants, measurements were obtained in "open" scenery; 24 participants from this group took part in tests with scenery movement frequencies of 0.2 Hz and 0.5 Hz, with the remaining 16 participating in tests with scenery movement frequencies of 0.7 Hz and 1.4 Hz.
- for a group of 43 measurements were obtained in "closed" scenery, with 32 participants tested at scenery movement frequencies of 0.2 Hz and 0.5 Hz and 11 participants tested at scenery movement frequencies of 0.7 Hz and 1.4 Hz

Analyzed quantities

The measurements obtained were the displacements of the COP for successive moments during the 30 s of testing. Analysis was performed using MATLAB software. In the first stage, analysis of the average velocity of the COP – total and in AP direction – and the COP range of motion in AP direction was performed. The results were compared for all conditions. In the next step, the frequency analysis of the measurements was performed by determining the PSD of the COP displacement in the AP direction, determined as the square of the amplitude values of the bands from the (FFT) calculations divided by the unit frequency. Then, the Trend Change Index (TCI) coefficient was calculated. This coefficient defines the number of changes in the trend, determined as the number of signal intersections from the Moving Average Convergence Divergence (MACD) calculation algorithm.

Calculation of TCI and MACD coefficients

The MACD is presented in the form of two lines: the MACD line and the signal line. The MACD line was obtained by subtracting two moving averages with exponential weights taking into account 12 samples (short-period) and 26 samples (long-period) (Eqs. (3) and (4)).

$$\mathrm{MACD}_{12,26} = \mathrm{EMA}_{12} - \mathrm{EMA}_{26}, \quad (3)$$

where:
EMA_{12} – faster exponential moving average,
EMA_{26} – slower exponential moving average;

$$\mathrm{EMA}_{pN} = \frac{p_0 + (1-\alpha)p_1 + (1-\alpha)^2 p_2 + (1-\alpha)^3 p_3 + \ldots + (1-a)^N p_N}{1 + (1-\alpha) + (1-\alpha)^2 + (1-\alpha)^3 + \ldots + (1-\alpha)^N}, \quad (4)$$

where:
p_0 – ultimate value,
p_1 – penultimate value,
p_N – 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 taking into account the nine MACD signal samples (Eq. (5)).

$$\text{Signal Line} = \mathrm{EMA}_{\mathrm{MACD},9}. \quad (5)$$

The intersection of the MACD and signal line signals marks a trend change in the COP displacement signal in the AP direction. A graphical interpretation of the crossings for the COP signal is shown in Fig. 3. Changes in the trend are related to the change in the direction of the COP movement. The TCI coefficient is the number of changes in the signal trend during a 30 s test, calculated as the sum of the MACD and signal line crossings.

Comparative analysis of the PSD and MACD

The calculated values of the PSD and MACD coefficients were used to analyze the influence of the disturbances participants were exposed to. The analysis compared both the effects of particular scenery and the frequency of oscillations on the participants, as well as the differences in relation to the real environment. Both PSD and MACD calculations were made for the AP direction.

The MACD coefficient made it possible to determine the number of changes in the trend throughout the entirety of every 30 s measurement. Detailed analysis showed that timespans differed between individual changes in the trend. Therefore, the detected trend changes were grouped according to the time preceding these changes and according to the ranges indicated in row T of Table 1. To make comparative analysis of the MACD ratio with the calculated PSD possible, the time intervals obtained for MACD were converted into corresponding frequencies using the following assumptions:

- the time of the COP skips between two consecutive positions detected as a trend change was treated as a half of the whole cyclic movement in the forward or backward direction;
- in the case of a cyclical movement, the time before the detected trend change was half of the full cycle (i.e., it takes half of the period); hence, the period was twice the measured time preceding the detected trend change;

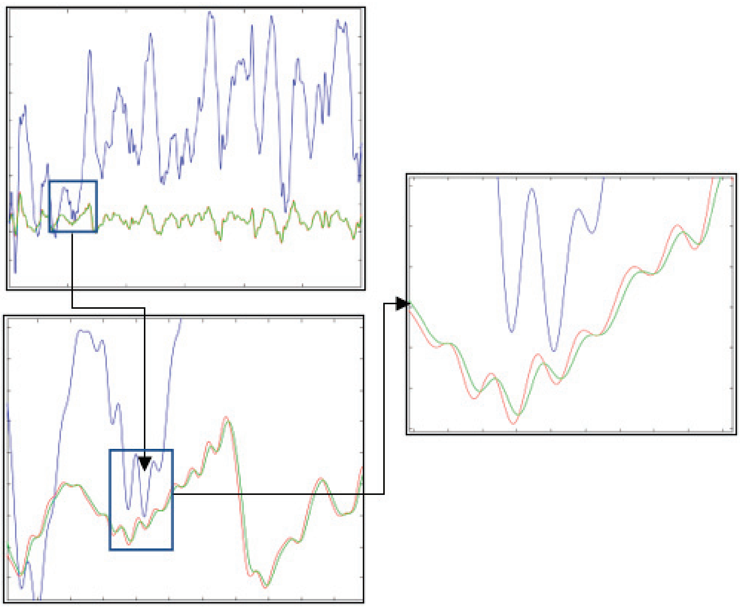


Fig. 3. Signal line and MACD waveforms for an exemplary COP waveform.
The intersections of the MACD and signal line signals mark the locations of the trend changes in the COP signal

Table 1. The time intervals considered during the analyzes
and the corresponding frequency intervals of the COP displacement signal

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 frequency of such a cyclic component was calculated in accordance with Eq. (6).

$$f = \frac{1}{2t_p}, \tag{6}$$

where:
f – frequency,
t_p = time between consecutive detected trend changes with $2t_p$ = period.

It should be emphasized that detected changes in the trend can be both cyclical and non-cyclical, whilst the presented conversion is intended to group the obtained results of the calculations in a manner that enables the comparative analysis of MACD and PSD. The summary of the analyzed time intervals and the corresponding frequencies is presented in Table 1. During analyzes of PSD values the total power was determined for ranges of 0.1–0.5 Hz and 0.5–10 Hz, as well as for 0.5–10 Hz divided into intervals, as shown in Table 1. MACD coefficients were determined in total for the range 0.5–10 Hz and with division into intervals according to Table 1. The MACD coefficients for the range below 0.5 Hz for the parameters adopted in the calculations were zero. This means that no trend changes where the time was longer than 1 s were detected.

Statistical analysis

The statistical analysis of the results was performed with use of the Statistica 13 software. In the first step of the analysis, the occurrence of normal distributions for each of the compared values was tested for using the Shapiro–Wilk test. The results did not confirm the presence of normal distributions in all subgroups, hence, the graphs show the median for the calculated values. In the next step, the Kruskal–Wallis ANOVA test and Dunn's post-hoc test were performed to investigate whether there were significant statistical differences in the analyzed groups.

3. Results

The measured values of successive COP positions in time were developed using analyzes in time and frequency domains and on the basis of algorithms for determining stock exchange coefficients. In Table 2, the basic time-domain calculations that are among the most frequently analyzed variables in balance maintenance ability tests (i.e., the resultant average COP velocity, the average COP velocity in the AP direction and the range of motion in the AP direction) are shown. The results presented from analyzes in the time domain show a statistically significant increase in the values measured during the test in the virtual environment in relation to tests in the real environment for all measurements except for:

- results of the average total COP velocity and average velocity in the AP direction when comparing the measurements with EC with measurements in "open" and "closed" scenery with oscillation frequencies of 0.2 Hz;
- the range of motion in the AP direction when comparing measurements made in the real environment (both EO and EC) with measurements in "open" scenery with oscillation frequencies of 0.2 Hz and 0.5 Hz.

In Figure 4a, the calculated PSD values for the ranges above and below 0.5 Hz are shown. Despite the noticeable differences between the values obtained for individual types of measurements, In Table 3, it is shown that statistically significant differences occur only in the case of:

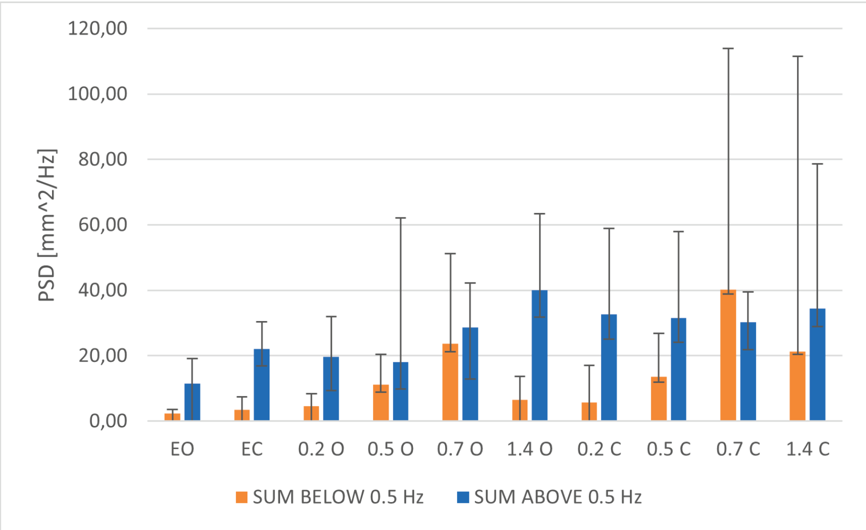
- comparisons of tests with EO in relation to all other measurements for both frequency ranges;
- the frequency range of 0.5–10 Hz, the comparison of tests with EC in relation to measurements in "open" scenery with a scenery oscillation frequency of 0.7 Hz and in "closed" scenery with scenery oscillation frequencies of 0.5 Hz, 0.7 Hz and 1.4 Hz;
- the frequency range below 0.5 Hz, comparisons of tests with EC for all measurements except for measurements in "open" scenery where the scenery oscillated at frequencies of 0.2 Hz and 0.5 Hz.

Comparison of measurements made in the virtual environment with each other did not show statistically significant differences.

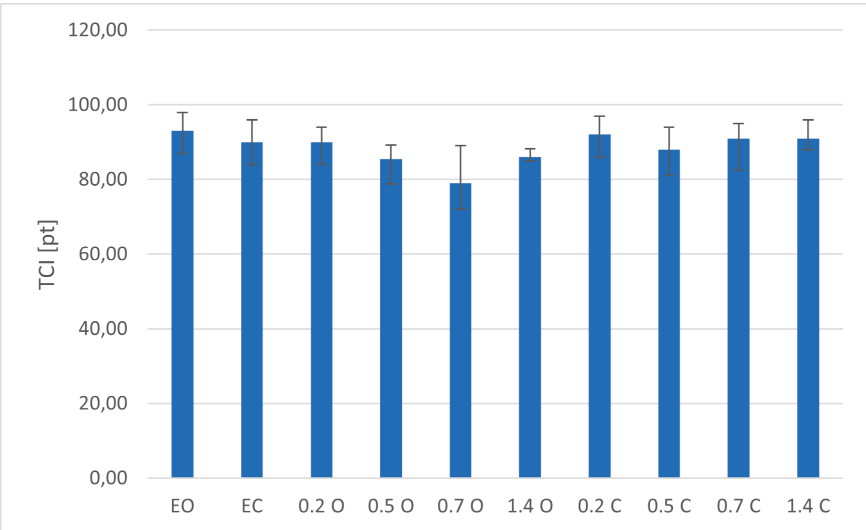
Comparing the PSD values obtained in individual intervals above and below 0.5 Hz (Table 3) showed statistically significant differences for all measurements except for measurements in "open" scenery with the

Table 2. Values obtained in the time domain: V = average velocity of Center of Pressure, V_AP = average velocity of COP in AP direction, R_AP = range of motion of COP in AP direction

	EO	EC	0.2 O	0.5 O	0.7 O	1.4 O	0.2 C	0.5 C	0.7 C	1.4 C
V	7.6	9.0	10.8	12.0	14.2	11.6	9.7	11.4	13.7	20.5
V_AP	4.6	5.8	7.0	7.6	11.3	8.2	6.9	8.5	10.7	16.7
R_AP	17.0	17.2	19.6	19.0	27.3	23.9	21.7	23.3	38.0	31.5



(a)



(b)

Fig. 4. (a) PSD values obtained for frequencies above and below 0.5 Hz, (b) TCI values for time intervals corresponding to frequencies above 0.5 Hz

Table 3. The p values ($\alpha = 0.05$) obtained for the comparison of the PSD results for tests in real and virtual environments

Measurement	EO	EC	0.2 O	0.5 O	0.7 O	1.4 O	0.2 C	0.5 C	0.7 C	1.4 C
	above 0.5 Hz									
EO		0.044	0.015	0.000	0.000	0.006	0.000	0.000	0.000	0.000
EC	x	x	0.926	0.201	0.001	0.613	0.418	0.000	0.000	0.000
	below 0.5 Hz									
EO		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
EC	x	x	0.130	0.081	0.008	0.001	0.003	0.000	0.015	0.035
	comparison between results above 0.5 Hz and below 0.5 Hz									
	0.000	0.000	0.000	0.000	0.501	0.004	0.000	0.003	0.071	0.136

Legend: EO – eyes open; EC – Eyes closed.

scenery oscillation at 0.7 Hz and in "closed" scenery with the scenery oscillation at 0.7 Hz and 1.4 Hz.

In the case of summary analyzes of the values of the TCI coefficient calculated for individual types of tests (ranges above 0.5 Hz), the obtained values are similar (Fig. 4b) and no statistically significant differences were observed.

It is noteworthy that the very large values of the coefficients of variation (CV) (Table 4) obtained in the case of PSD analyzes in relation to similar analyzes made with the use of the TCI coefficient.

Analyzing the effect size for Dunn's post-hoc test, all achieved values of the *r* (epsilon square) parameter exceed the value of 0.38. In the interpretation proposed by Rea and Parker [18] it means "strong" effect size. The result means that we can consider the results of the comparisons as valid for the current research group.

In Figures 5 and 6, the median number of trend changes recorded in individual measurements, divided into frequency ranges corresponding to the ranges in Table 1, are shown. Comparison of the measurements carried out with EO with those carried out with EC showed no statistically significant differences for any of the intervals (Table 5). When comparing measurements obtained in the real environment (EO and EC) with measurements obtained in the virtual environment, statistically significant differences were observed primarily with scenery oscillations at frequencies of 1.4 Hz and of 0.7 Hz and regardless of the type of scenery used (Table 5). When comparing the measurements made in the virtual environment with each other, statistically significant differences were found only when comparing tests performed with a scenery oscillation frequency of 1.4 Hz with tests performed at other frequencies.

In the case of the figures in which the values of median PSD from individual measurements with division into frequency ranges are shown (Figs. 7 and 8), it can be seen that the maximum values were obtained

Table 4. Coefficient of variation obtained for total PSD for frequency ranges below and above 0.5 Hz and TCI for frequencies above 0.5 Hz

CV of:	EO	EC	0.2 O	0.5 O	0.7 O	1.4 O	0.2 C	0.5 C	0.7 C	1.4 C
PSD 0–0.5 Hz [%]	57.1	37.6	49.9	142.5	38.1	49.0	53.2	58.4	24.1	91.2
PSD >0.5 Hz [%]	50.4	73.9	57.7	79.9	95.4	72.7	119.9	73.9	122.7	227.0
TCI [%]	5.9	6.7	5.5	6.1	10.7	1.9	6.0	7.4	6.9	4.4

Legend: EO – eyes open; EC – Eyes closed.

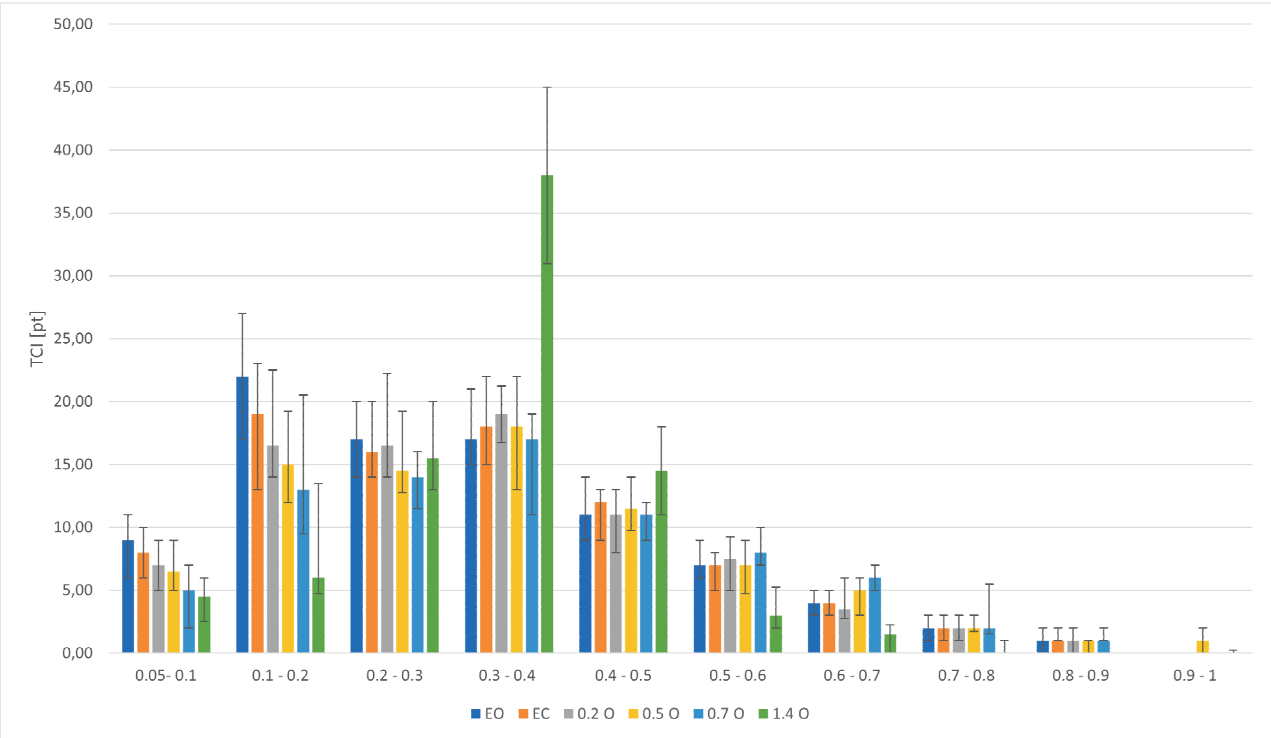


Fig. 5. TCI for individual time slots for measurements in the real environment and the open scenery

in measurements with scenery oscillation frequencies of 0.7 and 1.4 Hz in intervals corresponding to these frequencies and regardless of the type of scenery. Also, in the case of tests with the scenery oscillating at a frequency of 0.5 Hz, the increase in the PSD value in the range corresponding to this frequency is noticeable. The remaining PSD values, especially in the case of measurements in the real environment (Fig. 9), are negligibly small. The *p* values indicate statistically significant differences between the measurements in the real and virtual environment are presented in Table 6. In the case of comparing the measurements in the virtual environment between themselves, statistically significant differences were obtained only when the measurements

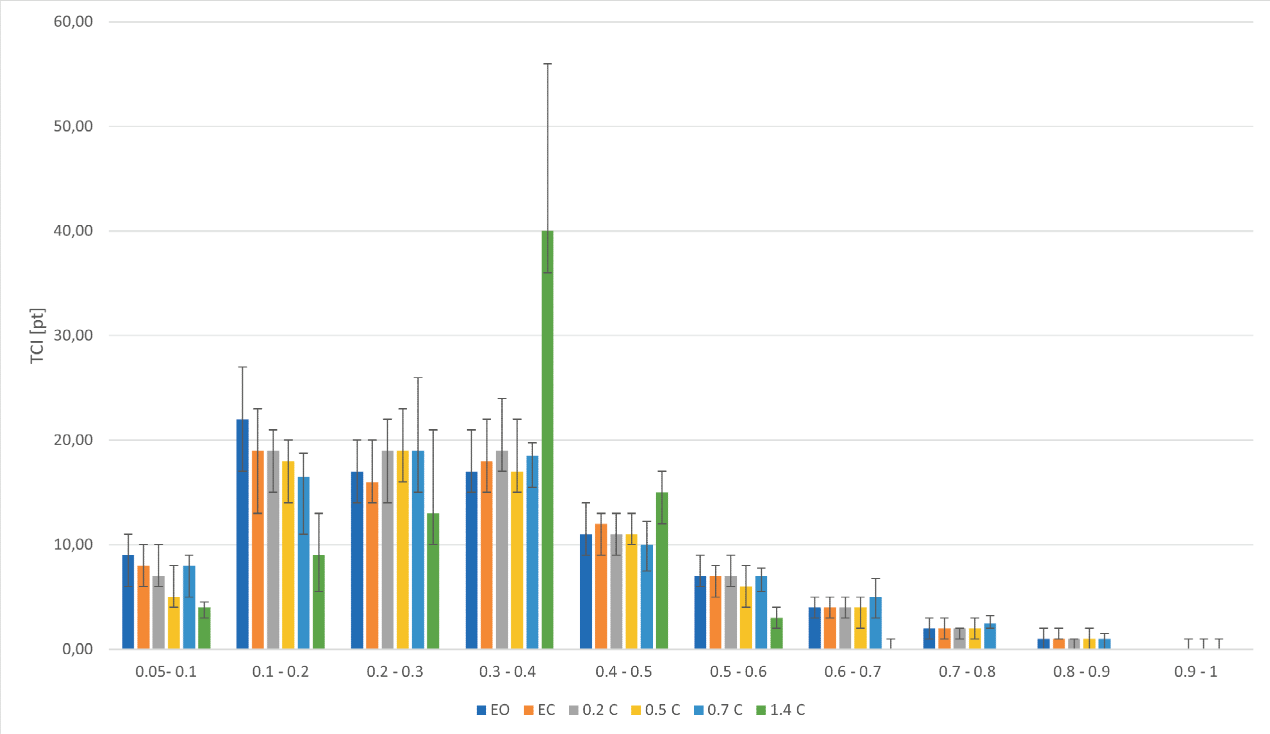


Fig. 6. TCI for individual time intervals for measurements in the real environment and in the closed scenery

Table 5. *p* values ($\alpha = 0.05$) for comparison of TCI between individual studies

Research	Time interval [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	0.6–0.7	0.7–0.8	0.8–0.9	0.9–1.0
EO	EC	0.959	0.176	1.000	0.839	1.000	0.901	1.000	1.000	0.889	1.000
EO	0.2 O	0.484	0.308	1.000	0.861	0.994	1.000	1.000	1.000	0.985	1.000
EO	0.5 O	0.557	0.005	0.932	1.000	1.000	1.000	0.933	0.995	1.000	0.672
EO	0.7 O	0.002	0.004	0.426	0.998	0.983	0.987	0.020	0.931	0.579	0.979
EO	1.4 O	0.000	0.000	0.999	0.000	0.118	0.000	0.017	0.004	0.043	0.905
EO	0.2 C	0.808	0.370	1.000	0.493	1.000	1.000	1.000	0.978	0.999	1.000
EO	0.5 C	0.004	0.126	0.829	0.988	1.000	0.414	1.000	0.985	1.000	1.000
EO	0.7 C	0.947	0.173	0.986	1.000	0.950	1.000	0.950	0.965	1.000	1.000
EO	1.4 C	0.000	0.000	0.919	0.000	0.580	0.000	0.000	0.000	0.044	0.186
EC	0.2 O	0.951	1.000	1.000	1.000	1.000	0.979	0.999	1.000	1.000	1.000
EC	0.5 O	0.971	0.563	0.942	1.000	1.000	1.000	0.992	0.996	0.863	0.799
EC	0.7 O	0.025	0.341	0.447	0.755	0.997	0.665	0.055	0.933	0.976	0.948
EC	1.4 O	0.001	0.000	0.999	0.000	0.062	0.005	0.006	0.004	0.002	0.830
EC	0.2 C	0.999	1.000	1.000	0.995	1.000	0.823	1.000	0.978	0.684	1.000
EC	0.5 C	0.094	0.998	0.807	1.000	1.000	0.979	1.000	0.984	1.000	1.000
EC	0.7 C	1.000	0.939	0.983	1.000	0.984	1.000	0.990	0.966	1.000	1.000
EC	1.4 C	0.001	0.001	0.927	0.000	0.433	0.001	0.000	0.000	0.003	0.129

Legend: EO – eyes open; EC – Eyes closed.

with the scenery oscillating at frequencies of 0.2 Hz and 0.5 Hz were compared with the measurements taken with the "closed" scenery oscillating at a frequency of 1.4 Hz. Tables 7–9 contain the calculated CVs obtained for individual measurements. It is also worth noting that the values of these coefficients obtained for changes in the trend are smaller in the case of the number of changes in the trend than in the case of PSD, especially in the case of high frequencies.

Table 6. p values ($\alpha = 0.05$) for the comparison of PSD results between studies in real and virtual environments

Research \ Time interval [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	0.6–0.7	0.7–0.8	0.8–0.9	0.9–1.0
EO	EC	0.005	0.018	0.001	0.011	0.018	0.010	0.754	0.998	0.483	0.011
EO	0.2 O	0.056	0.280	0.006	0.010	0.027	0.217	0.208	0.106	0.064	0.003
EO	0.5 O	0.003	0.004	0.001	0.000	0.000	0.002	0.021	0.386	0.061	0.000
EO	0.7 O	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.101	0.026
EO	1.4 O	0.000	0.000	0.001	0.000	0.052	0.109	0.648	0.994	0.885	0.300
EO	0.2 C	0.000	0.000	0.000	0.000	0.000	0.000	0.027	0.017	0.002	0.005
EO	0.5 C	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
EO	0.7 C	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.045	0.079
EO	1.4 C	0.000	0.000	0.000	0.000	0.000	0.000	0.015	0.008	0.006	0.292
EC	0.2 O	1.000	1.000	0.996	0.967	0.989	1.000	0.913	0.363	0.826	0.861
EC	0.5 O	0.928	0.868	0.915	0.286	0.288	0.809	0.419	0.770	0.817	0.008
EC	0.7 O	0.121	0.033	0.058	0.017	0.007	0.064	0.000	0.000	0.796	0.948
EC	1.4 O	0.387	0.170	0.784	0.000	0.974	0.998	0.995	1.000	1.000	1.000
EC	0.2 C	0.850	0.242	0.449	0.298	0.144	0.751	0.577	0.116	0.320	0.983
EC	0.5 C	0.244	0.003	0.005	0.003	0.006	0.071	0.000	0.002	0.024	0.000
EC	0.7 C	0.007	0.003	0.001	0.011	0.006	0.009	0.000	0.000	0.483	0.961
EC	1.4 C	0.000	0.000	0.001	0.000	0.003	0.014	0.182	0.032	0.161	0.999

Table 7. Coefficient of variation in individual measurements in the real environment

CV \ Time interval [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	0.6–0.7	0.7–0.8	0.8–0.9	0.9–1.0
eyes open										
PSD	30.1	52.6	68.4	58.9	67.1	62.5	88.8	51.7	73.6	92.1
TCI	27.8	22.7	17.6	17.6	22.7	21.4	25.0	50.0	100.0	–
eyes closed										
PSD	41.9	55.9	65.0	64.3	62.2	75.2	90.9	125.1	86.3	100.5
TCI	25.0	26.3	18.8	19.4	16.7	21.4	25.0	50.0	50.0	

Table 8. Coefficient of variation in individual measurements in the virtual environment in "open" scenery

CV \ Time interval [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	0.6–0.7	0.7–0.8	0.8–0.9	0.9–1.0
open scenery 0.2 Hz										
PSD	24.3	48.8	48.8	44.8	64.8	51.2	88.7	105.0	89.2	72.2
TCI	28.6	25.8	25.0	11.8	22.7	28.3	46.4	50.0	100.0	
open scenery 0.5 Hz										
PSD	33.3	49.0	65.6	120.7	108.5	82.9	112.3	99.0	108.0	85.1
TCI	30.8	24.2	22.4	25.0	18.5	30.4	30.0	31.3	50.0	100.0
open scenery 0.7 Hz										
PSD	73.9	51.6	110.7	99.7	87.4	59.8	137.9	89.7	57.7	47.4
TCI	50.0	42.3	16.1	23.5	13.6	18.8	16.7	100.0	50.0	
open scenery 1.4 Hz										
PSD	20.7	64.5	62.0	62.2	60.4	41.5	66.6	71.7	94.7	94.1
TCI	38.9	72.9	22.6	18.4	24.1	54.2	75.0			

Table 9. Coefficient of variation in individual measurements in the virtual environment in "closed" scenery

CV \ Time interval [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	0.6–0.7	0.7–0.8	0.8–0.9	0.9–1.0
closed scenery 0.2 Hz										
PSD	43.6	116.7	111.8	124.7	63.9	104.7	89.3	101.7	54.7	73.1
TCI	28.6	15.8	21.1	18.4	18.2	21.4	25.0	25.0	50.0	
closed scenery 0.5 Hz										
PSD	62.5	66.8	93.4	123.8	89.5	75.5	150.6	70.9	106.9	76.5
TCI	40.0	16.7	18.4	20.6	13.6	33.3	37.5	50.0	100.0	
closed scenery 0.7 Hz										
PSD	233.2	430.4	202.8	337.4	202.0	167.6	143.2	112.7	81.1	52.0
TCI	25.0	23.5	28.9	11.5	23.8	16.1	37.5	25.0	75.0	
closed scenery 1.4 Hz										
PSD	96.2	124.9	121.7	213.7	343.8	142.4	193.2	214.3	242.7	397.9
TCI	18.8	41.7	42.3	25.0	16.7	33.3				

4. Discussion

The analysis of successive positions of the COP in terms of the path length it traveled during the measurement, the average speed with which it was moving, the area in which it was located or the range of displacements along a specific direction are the simplest and most common methods of assessing the ability to maintain balance. In a person with balance dysfunctionalities these values increase, which, in turn, allows for a preliminary diagnosis of problems with balance or the assessment of progress in rehabilitation. However, these approaches do not always work well. Use of an unstable surface or conditions causing sensory conflict cause all these values to increase in healthy people. In such cases, analysis in the frequency domain becomes helpful, as it enables the decomposition of the COP movement signal into cyclic components and thus allows for the determination of the frequen-

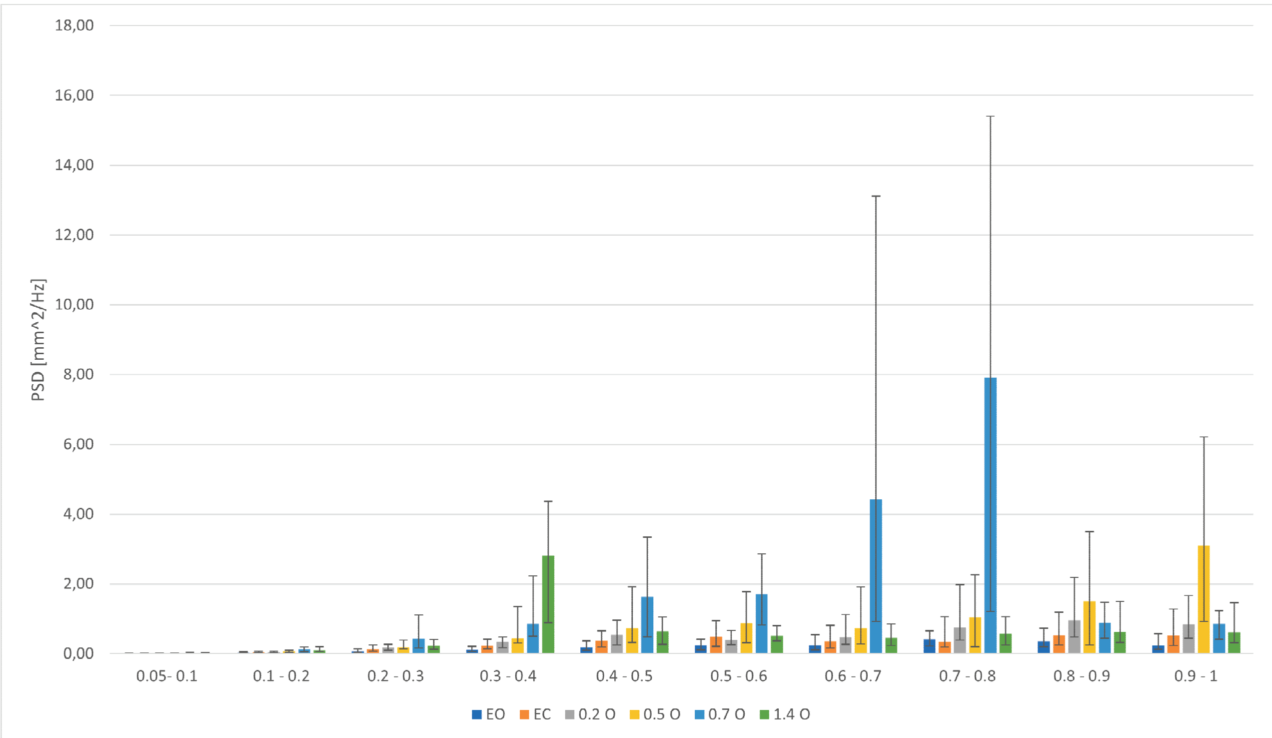


Fig. 7. PSD values obtained for individual time intervals for measurements in the real environment and in the open scenery

cies of the main movement components. In this way, components of movement such as the body following a cyclically moving environment become visible, which, in turn, increases the possibilities for interpreting the received signal [12], [21]. However, the observation of successive positions of the COP indicates that the continuous correction of the position, velocity and acceleration of the COM, and the resulting changes in the position of the COP may not only be cyclical but also random. Both traditional time domain methods and frequency domain analysis cannot detect such non-cyclic corrections. The technical analyzes proposed in this paper for determining the trend changes in currency exchange rates and stock market shares made it possible to detect the trend changes occurring in the COP movement (i.e., significant changes in the direction of the movement of this point), the nature of which was both cyclical and non-cyclical. As part of

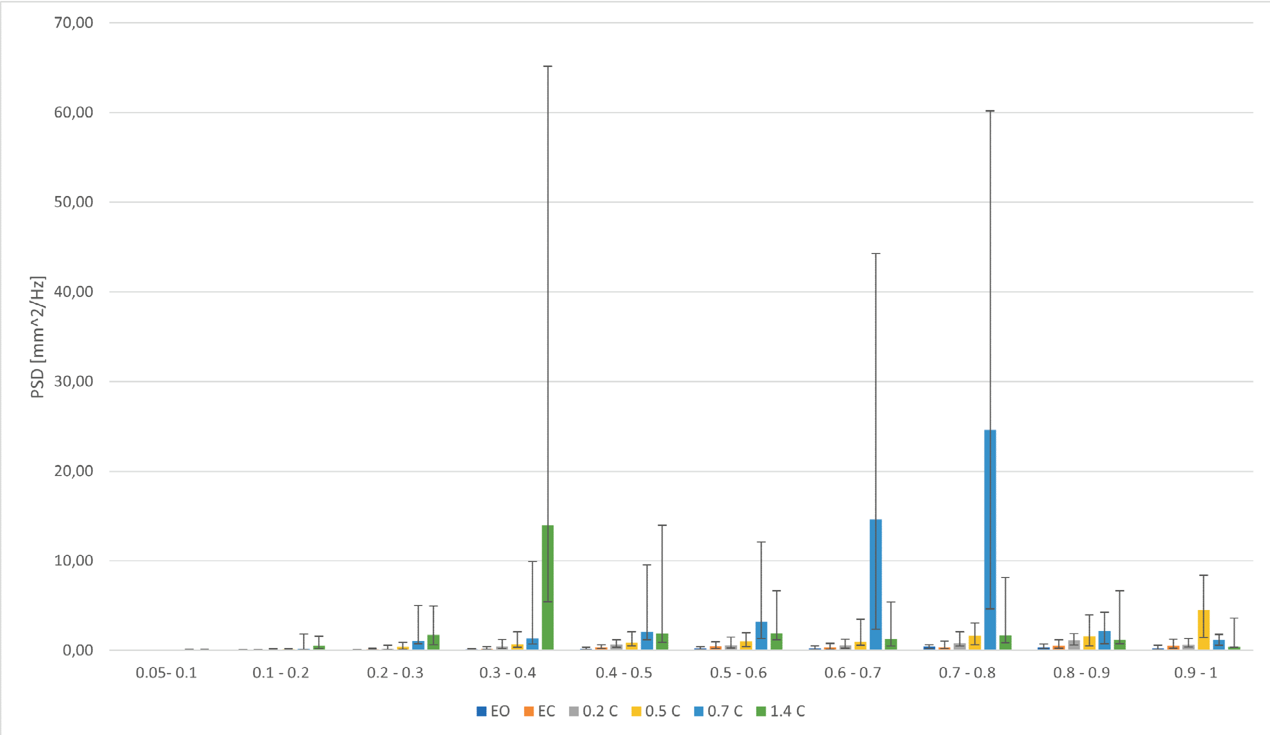


Fig. 8. PSD values obtained for individual time intervals for measurements in the real environment and in a closed scenery

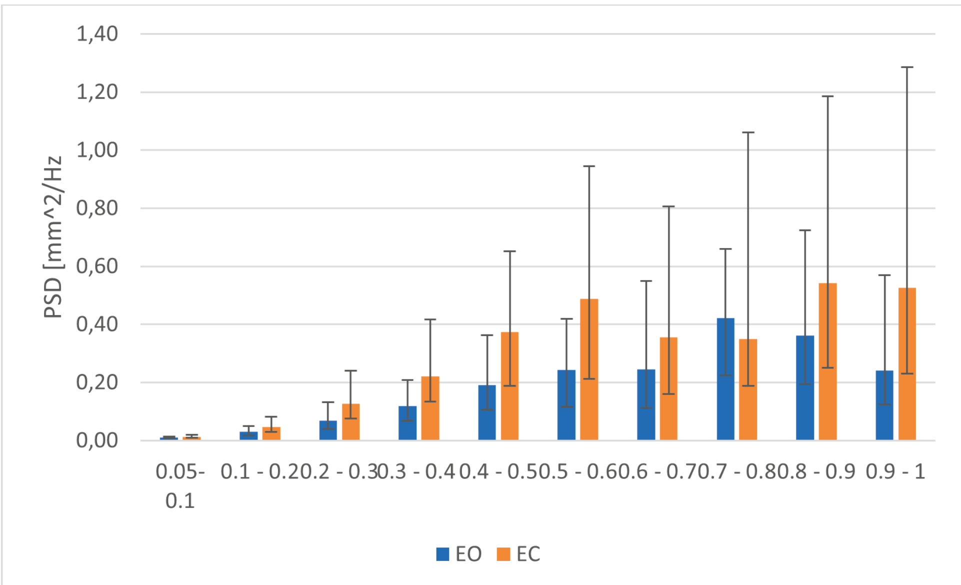


Fig. 9. PSD values obtained for individual time intervals for measurements in real environment

the work, comparative analyzes were carried out in the field of time and frequency using calculations used for stock market analyzes in order to present the interpretative possibilities of these approaches in the assessment of the ability to maintain balance. Calculations for a new coefficient that defines the number of trend changes in the COP displacement signal were proposed.

Analysis of individual measurements

The analysis of the results obtained in the time domain shows that the introduction of oscillating scenery increases the values of the analyzed quantities in the real environment. Both the speed and the range of motion increased, however, these values do not make it possible to indicate the mechanism of these changes (Table 2).

PSD is used to indicate the dominant frequencies in the analyzed signal, especially in the cases where a large amount of noise is present. The PSD presented in Fig. 4a shows values below 0.5 Hz and above 0.5 Hz and indicates that the majority of cyclic components appearing in the analyzed signal have a frequency lower than 0.5 Hz. The analysis of *p* coefficients (Table 3) showed no statistically significant differences with the scenery oscillating at a frequency of 0.7 Hz for both types of scenery and for "closed" scenery with an oscillation frequency of 1.4 Hz. This indicates that, for these cases, the values of the COP motion amplitude resulting from the body following the moving scenery were so large that they were visible in the frequency range above 0.5 Hz. This result seems to be consistent with the conclusions of other studies [12], [21]. Such a distribution of cyclic components may indicate the dominance of visuo-vestibular control [2], [15], when the body performs mainly slow, cyclic movements while standing. The increases in the PSD value in the case of research in the virtual environment may indicate the appearance of additional cyclical movements related to the oscillation of the scenery. These changes include both increases at frequencies lower than 0.5 Hz and higher than 0.5 Hz – the latter case is particularly visible in measurements conducted in "closed" scenery with the oscillation frequencies of this scenery equal to 0.7 Hz and 1.4 Hz. Analysis of the data presented in Figure 8 shows that this increase is mainly caused by increases in the PSD value in the time interval of 0.3–0.4 s for the test with a frequency of 1.4 Hz and the time interval of 0.6–0.8 s for the test with a frequency of 0.7 Hz. Such PSD may show that the "closed" scenery together with the higher oscillation frequency had a greater influence on the behavior of the participants, causing them to have significant cyclic movements synchronized with the oscillation of the scenery.

The analysis of the sum of individual trend changes for individual measurements (Fig. 4b) shows that the number of these changes does not depend on the conditions. This may mean that balance control requires a certain number of rapid changes in the trend of the COP movement (for the time interval of 0.05–1.0 s, corresponding to frequencies of 10 Hz to 0.5 Hz). Making the conditions less favorable, which can include the introduction of a disturbance in the form of oscillating scenery, does not significantly change this number. On this basis, it can be concluded that either the balance system does not need more of this type of movement or the locomotor system is not able to generate more of them.

One more conclusion can be drawn from the PSD analysis and the sum of trend changes. The values of the CVs (Table 4) obtained for PSD only in the case of measurements with EC and for measurements at a frequency of 0.7 Hz (in both cases for a result below 0.5 Hz) take a value lower than 40%. In the rest of cases, they are close to or much greater than 50%. This demonstrates a large dispersion of the obtained measurement data. In the case of the number of changes in the trend, these values exceed 10% only in one case. This may indicate that in this type of analysis, when it is important to study insignificant but rapid movements of the COP, the use of analyzes based on stock exchange ratios may bring much better results.

Analysis with division into time intervals

Observed signal power in the range above 0.5 Hz obtained in tests performed in the real environment (Fig. 9), as well as in tests in the virtual environment with the scenery oscillating at a frequency of 0.2 Hz and 0.5 Hz (Figs. 7, 8), is negligibly small and does not exceed most of the analyzed unity intervals. The exception is the range of 0.8–1.0 s, where slightly higher PSD values obtained during tests at a frequency of 0.5 Hz were observed. This can be explained by the fact that the time interval of 0.8–1.0 s corresponds approximately to this frequency (i.e., the movements of the body following the scenery were observed here).

In the case of frequencies of 0.7 Hz and 1.4 Hz, a significant increase in the PSD value was observed in the time intervals corresponding to these frequencies (0.3–0.4 s for the frequency of 1.4 Hz and 0.6–0.8 s for the frequency of 0.7 Hz). These increases indicate that the COP, and thus the entire body, followed the cyclically moving scenery. The differences in the PSD values visible between the "open" and "closed" scenery result from differences in the amplitude values of the recorded movements following the scenery.

The analysis of the number of trend changes obtained during the tests in the real environment (Figs. 5, 6) shows that in the intervals from 0.05 s to 0.5 s (which corresponded to the frequency range of 0.5–10 Hz movements) there was a significant number of changes in the trend indicating changes in the direction of the COP movement; this was despite very low PSD values. According to the information provided by Bizid et al. [2] and Micarelli et al. [15], this may indicate an important role of proprioceptive control, despite the PSD analysis indicating a lack of cyclic movements in this frequency range and suggesting that there is a minor role for this type of control.

Interesting conclusions are provided by analysis of the number of trend changes in subsequent time intervals obtained in the virtual environment in relation to results obtained in the real environment (Figs. 5, 6). In the case of scenery oscillation frequencies of 0.7 Hz and 1.4 Hz for the time interval of 0.05–0.2 s, most cases saw a statistically significant decrease in the number of trend changes observed compared to the measurements with EO and EC, with a simultaneous increase of this number in the time intervals corresponding to the scenery oscillation frequencies (0.3–0.5 s). For the frequency of 1.4 Hz, a drop in the number of trend changes was also recorded for the time interval of 0.5–0.9 s. This means that the increased number of trend changes appearing at the frequencies of 0.7 Hz and 1.4 Hz reduced the number of trend changes at other frequencies. When analyzing the possible causes of these changes, it is necessary to return to the previous point that stated the total number of changes in the trend for the 0.05–1.0 s range undergoes only very slight changes, regardless the measurement carried out (Fig. 4b). This may mean that the introduction of disturbances with a frequency in this range (e.g., 1.4 Hz) resulted in an increase in the number of body movements performed with this frequency (in an attempt to follow the scenery to prevent a potential fall) and forced a reduction in the number of trend changes in other time periods, whilst the total the number of all trend changes remained approximately constant. It can be assumed that this invariability in the maximum number of trend changes may be related to the fact that the locomotor system is not able to increase the total number of trend changes above a certain value. In such case, introducing environmental oscillations with a specific frequency may reduce the number of trend changes in the range of 0.05–0.2 s, where these fast movements of COP are treated as related to proprioception. This reduction in the number of changes may not allow the proprioceptive system to obtain sufficient information and thus the individual may not be able to maintain their balance. This conclusion shows that cyclical oscillations of the environment not only affects the information collected by the visuo-vestibular system, but may also distort information from the proprioceptive system.

Additionally, it should be noted that the coefficients of variation obtained for the trend changes are much smaller than those obtained for the PSD (Tables 4–9), which may indicate that the analysis of these values provides much more reliable results. Based on the above considerations, it can be assumed that:

- reducing the number of trend changes in the frequency band assumed to be used in proprioceptive control may have an impact on the ability to maintain balance; this information and the practical use of stock exchange ratios can be helpful in the diagnosis of people with balance dysfunctionalities;
- by analyzing changes in the number of changes in the trend in individual time intervals, it is possible to selectively assess the impact of proprioceptive control on the overall ability to maintain balance.

Limitations

The presented method for assessing the ability to keep balance is an extension of the methods used so far, however, it also has some limitations and elements that require further research, including:

- stating the extent to which changes in the parameters used for the calculations of TCI will affect the final results;
- determining whether the application of this method will give comparable or more reliable results in the case of using parameters that enable the analysis of slow changes in the trend (below 0.5 Hz) compared to the analyzes carried out in the frequency domain (i.e., Fourier transform, wavelet analysis);
- checking whether a decrease in the number of changes in the trend in the range of 0.05–0.2 s (above 0.5 Hz) has a negative impact on the ability to maintain balance;
- investigating whether smaller fluctuations in the number of changes in the trend mean less impact of the oscillating environment on the individual.

5. Conclusions

Summing up, it can be stated that the application of approaches for determining stock exchange indices in the analysis of subsequent COP positions provides new information that can be used in the assessment of the ability to maintain balance. This knowledge can be used both in clinical studies on balance and in the development of new methods using this type of measurement. The values of the proposed index may be used to determine the excitation of systems responsible for maintaining balance, as they constitute an objective tool for determining the number of COP displacement corrections per unit of time. These types of indicators may be appropriate for clinical applications.

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