Acta of Bioengineering and Biomechanics
Vol. 24, No. 1, 2022

Original paper
DOI: 10.37190/ABB-01900-2021-01

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

PIOTR WODARSKI*, JACEK JURKOJĆ, MARTA CHMURA, GRZEGORZ GRUSZKA, MAREK GZIK

Department of Biomechatronics, Faculty of Biomedical Engineering, Silesian University of Technology, Gliwice, Poland.

Purpose: The purpose of the study was to determine how a stimulus presented in the virtual reality environment as a simulation of a fall off the stairs, triggers a loss of balance. The study also examined if the head movement measurements and the analysis in the frequency domain could increase the range of interpretation. *Methods*: 11 healthy individuals were tested, two [A1] were identified as more susceptible to the introduced disturbance, and one reported having dizziness, car sickness and fear of heights. Measurements of center of pressure (COP) and head positions were performed in the real and in the virtual environment. The beginning of the simulation was either unexpected or preceded by a signal. The analysis included standard parameters determined in time domain as well as the amplitude of the first harmonic from the fast Fourier transform (FFT). *Results*: The analysis did not reveal statistically significant differences between results obtained: in real and virtual environments, with and without the warning signal. It was possible to notice the effect of virtual disturbance in the three selected individuals; this was particularly evident in the analysis of the first harmonic of the FFT. *Conclusions*: The conducted tests revealed that the limitation of the analyses exclusively to the time domain could be insufficient for a comprehensive interpretation. The effect of introduced disturbance was particularly noticeable in the analysis of the first harmonic for head movement. The application of this parameter could enable a more accurate investigation of a strategy aimed at maintaining balance.

Key words: *virtual reality, postural stability, balance, frequency analysis*

1. Introduction

The ability to maintain balance is important in enabling independent life, the performance of everyday activities and in allowing individuals to work at heights or partake in competitive sports. Disturbed balance may indicate diseases of the nervous system or be the result of ageing. Difficulty in maintaining balance could lead to falls resulting in injuries, which may further worsen health conditions [4], [22]. It is estimated that falls may impact 30% of people older than 65 who live independently at home and more than 50% of people in retirement homes [17]. Since society is aging, the number of people at risk of falls could be expected to grow [11]. However, the risk of falling does not only affect the elderly and has particularly serious consequences for people working at heights. A fall from height is one of the most frequent reasons for injuries (48%) and death (30%) among all incidents occurring during work at heights [23]. Apart from irresponsible behavior and inexperience, an increased risk of falling from a height is connected with age, fatigue, insufficient sleep, and poor health [23]. All of these factors adversely affect concentration and may lead to disturbed balance, increasing the risk of falling.

Problems with balance can be permanent and can be manifested by noting changes in the values of parameters that indicate the ability to maintain balance. These can be verified in tests involving regular standing with eyes open or closed, as well as during

* Corresponding author: Piotr Wodarski, Silesian Uniwersity of Technology, Gliwice, Poland. Phone: 512998000, e-mail: piotr.wodarski@polsl.pl

Received: August 5th, 2021
Accepted for publication: August 26th, 2021

gait [2], [3], [10], [31], [33]. However, there are cases when problems with balance are caused by specific conditions in the environment or from specific behaviors. For instance, American football players developed problems with balance after quick right- and left-head movements [7]. The detection of such less obvious balance disturbances requires the extension of standard balance measurements to include simulations of events connected with work or the introduction of additional factors that could disturb balance. The information delivered to individual senses responsible for balance may be diversified during a conflict of sensory stimuli. This is why balance-related tests are increasingly performed using virtual reality technology, where the scenery and the manner of its presentation are used as balance disturbing stimuli [6], [9], [16], [19], [20].

The application of virtual reality makes it possible to simulate the visual conditions of balance loss or to trigger a balance destabilizing factor. Tests of visual stimulation and the effect of visual stimuli on posture control were performed under various conditions. These included individuals focusing on objects located at various distances [28] or being exposed to a moving environment [16], [25], [32]. Virtual reality (VR) creates an illusion where a test participant has the impression of being in a place other than where they really are [18]. The introduction of virtual surroundings while simultaneously maintaining immovable ground, exposes a person to sensory conflict. As a result, the body generates a kinetic response towards the visual disturbance. The analysis of such a response can be a valuable source of diagnostic information concerning disturbed balance [9], [20].

In tests of maintaining balance, analyzed parameters usually include center of pressure (COP) displacements, including the average COP velocity, the area of an ellipse, and the range of the COP movements in the anterior-posterior (AP) and mid-lateral (ML) directions [5], [12], [14]. Importantly, there are increases in the values of these parameters under conditions of conflicting sensory stimuli, however, these changes are not necessarily connected with disturbed balance [15], [16]. For this reason, there is a growing demand for new methods of measurements and analyses. One of the solutions involves completing a frequency analysis aimed at observing changes that may be unnoticeable during a standard analysis using a time domain [12], [16]. Force platform-related analyses are limited to the two-dimensional plane under feet. This is why some tests have involved the use of accelerometers to detect changes in the postural balance based on movements of the center of mass (COM) or other segments of the body [20], [21], [34]. This resulted in additional analysis of body movements for maintaining balance [24], [29].

1.1. Objective of the research

It seems necessary to apply extended methods and use an advanced mathematical apparatus for measuring the ability to maintain balance. However, this approach requires that there would be standardized procedures for such measurements and defined ranges of parameter values, taking the responses of healthy and ill individuals to introduced disturbance into account. For this reason, the purpose of the research work included the following:

- determination whether a simulated fall off the stairs may affect the posture,
- determination of whether the extension of analyses with a frequency-related analysis could increase the scope of interpretation in relation to analyses based on the time domain,
- determination of whether measurements of the head movements could supplement the COP measurements with information regarding the effect of the introduced disturbance factor on the ability to maintain balance,
- determination of whether the visual warning signal preceding the introduction of the balance-disturbing factor will trigger a change in the head movements and the COP displacement.

2. Materials and methods

2.1. Study group

The study group consisted of 10 test participants (7 females and 3 males) at an average age of 25 (SD = 3) and an average BMI of 23 kg/m^2 (SD = 3.3). Interviews of participants indicated that none had a history of an extreme lower limb injury or had any motor system dysfunction, balance disorder, or any other problem that could affect their balance.

An additional test participant, designated as pp3 (female, 25 years of age, BMI = 17.3 kg/m^2), declared that she suffered from intense car sickness, a fear of heights, and dizziness (when her eyes were closed).

Increased values of selected parameters for two individuals (designated as pp1 and pp2) suggested the presence of potential problems with maintaining balance or, at least, higher susceptibility to the introduced virtual disturbance. Therefore, these individuals were excluded from the group of individuals treated as healthy and were instead the subjects of a separate case study, along with the person suffering from balance maintaining problems (pp3).

This study was previously approved by the Ethics in Research Committee of the Academy of Physical Education in Katowice (protocol number 5/2020). Each of the study participants was informed of consent in accordance with the Ethics in Research Committee, as well as of the form and the course of the study. In each case, consent to participate in the study was expressed in oral form (written consent was not required).

2.2. Measurement stand

The study was performed using a measurement platform (WinFDM-S, Zebris, sample frequency 100 Hz, 2560 extensometer sensors, sensors area: 34 cm × 54 cm), and a VR HTC Vive headset. The VR application was prepared in the Unity 3D system and consisted of a simple scenery. In the application, the avatar (facing the stairs) was placed on the floor near the stairs. The scenery is presented in Fig. 1.

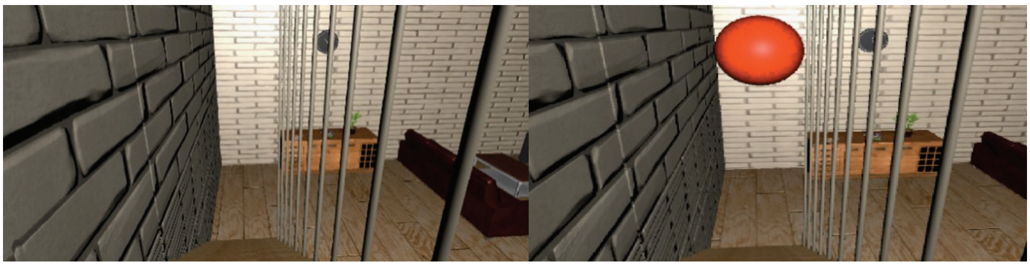

Fig. 1. The scenery of the test: without and with the warning signal

2.3. Experimental procedure

Measurements were taken of successive positions of the center of pressure (COP) (WinFDM-S) and successive positions of the head (HTC Vive). For head movement, the current position of the head was read directly from the Unity graphics engine from data obtained from the HTC Vive system. The results were used for a frequency analysis; the average COP velocity and the area of the ellipse containing the COP, were calculated.

The performance of the tests in the virtual reality trial was preceded by a trial of standing on the platform, where participants had their eyes open (EO) and closed (EC) for 60 seconds. Afterward, the participants took part in tests involving virtual reality (BB). The first 20 seconds of the tests involved leaning in the ML direction to synchronize the measurement systems. From the 20th second onwards, the patients stood still. At the 30th second, the system showed the movement of the scenery, simulating the fall off the stairs. For 20 seconds following the disturbance, the subject was supposed to stand without moving. In the subsequent test (BZ), the measurement procedure was the same as BB, except that participants were exposed to a visual red signal three seconds before the disturbance was triggered. The tests were subsequently repeated three times, obtaining data designated as BB1, BZ1, BB2, BZ2, BB3, and BZ3. During each of the measurements, the participant was supposed to stand motionless with their arms crossed on their chest.

2.4. Analysis of results

The positions of the COP and the head on the platform plane and in space were recorded. The analyses included parameters identified as changes in the direction of the triggered visual disturbance (i.e., AP). Displacements in the ML direction were only used to synchronize related courses and were not analyzed. The values recorded during the first 20 seconds were not analyzed and were only used for time synchronization of the results. The analysis involved measuring the changes of the COP displacements and head movements and adopting the 20th second (the end of the synchronizing procedure) as the zero moment of the test.

The analysis of the obtained measurement data was divided into three stages (Fig. 2).

The first stage involved identifying the effect of disturbance based on comparison of the average velocity of the COP displacements and head movements (V), and the area of the ellipse (EA) in relation to the

COP and the head. The comparison of the test results included the EO, EC, BB1, BB2, BB3 and BZ1, BZ2, BZ3 tests.

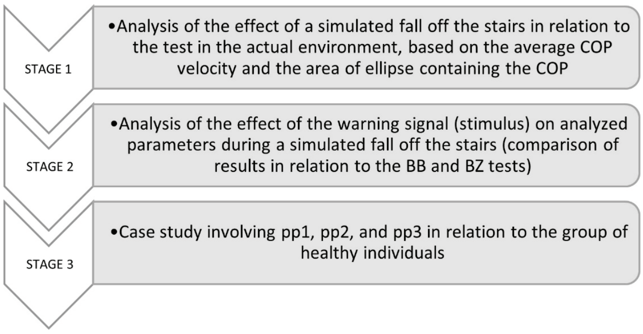

Fig. 2. Stages of analysis of the results

The second stage involved the analysis of the COP displacements and head movements in the AP direction in the time domain and frequency domain. The aim of the analysis was to identify the impact of the warning signal (stimulus) on the test participants' responses to the disturbance. The analysis included the average velocity, the area of the ellipse, and the range of movements in the AP direction, for both the COP and the head. The range of the COP and head movements was calculated as the difference of the coordinates of two extreme positions in the AP direction, within 15 seconds following the introduction of disturbance (recorded after a three second disturbance). The displacement values were designated as D_{AD}. The COP displacement and head movement values in the AP direction were used for the frequency analysis by calculating the fast Fourier transform. The first harmonic amplitude (A1h) was identified from an analysis of the spectrum. Supplementing the analysis in the time domain with the frequency domain enabled examination of the periodicity of the movements.

It was necessary to compare values to establish whether the following results: V, EA, D_{AD}, and A1h, changed in successive trials (three repeated tests in relation to BB and BZ). The results revealed statistically nonsignificant differences between the values of the parameters in subsequent tests. This result led to a decision to combine values of the BB1, BB2, and BB3 tests into one BB group as well as to combine values of the BZ1, BZ2, and BZ3 tests into one BZ group. The lack of statistically significant differences in subsequent measurements (all of the obtained *p*-values from the Kruskal–Wallis test were higher than a confidence threshold of 0.05 in all of the tests) made it possible to group all of the measurement results into two sets (BB and BZ) and perform further analyses taking into account the increased size of the groups.

An analysis of differences between the range of the COP displacements and the range of head movements triggered by the visual disturbance was completed. This was done by comparing parameter values after the introduction of disturbance, i.e., D_{AD}, and A1h for the COP and the head, for each of the tests.

The analysis made it possible to establish whether the visual warning signal/stimulus affected the behavior of test participants. The Shapiro–Wilk test was used for the BB and BZ groups and to perform comparative tests. This non-parametric test was conducted because of the small group size and the lack of a normal distribution. All calculations were performed using the Statistica, version 13, software program.

The third stage of analysis encompassed a case study comparing parameters for the individuals potentially having difficulty maintaining balance with those of the persons declaring a lack of balance-related problems.

3. Results

The first stage of the analyses used measurements in the real environment and involved the calculation of the average velocity (V) of the COP displacements and the values of the ellipse area (EA) containing the COP. The test results are presented in Table 1.

Table 1. Average COP velocity and the area of ellipse obtained in relation to the EO and EC tests (in relation to the pp1, pp2, and pp3 tests; the values indicate the median of 3 measurements)

	V [mm/s]		Ellipse area COP [mm^2]	
	EO	EC	EO	EC
Median	11.5	11.6	107	151
Lower quantile	9.3	10.4	76	80
Upper quantile	12.8	14.0	172	196
Minimum	7.9	8.1	67	40
Maximum	14.0	19.8	558	696
pp1	11.2	12.4	406	661
pp2	9.9	9.2	98	107
pp3	16.1	11.1	230	567

The average velocity of the COP and the head, the ellipse area containing the COP and head positions, and the ranges of the COP and head movements in the AP direction (D_{AD}), measured in the virtual environment were calculated (Table 2). The amplitude of the first harmonic in the fast Fourier transform (FFT) spectra was also calculated based on the frequency

Table 2. Values of velocity (V), range of movements in the AP DAD direction, the ellipse area calculated based on the ranges of the COP displacements, and head movements for the BB and BZ tests (the values indicate the median of 3 measurements in relation to the pp1, pp2, and pp3 tests)

	V 25s from the loss of balance				D_{AD} [mm]				Ellipse area [mm^2]			
	BB		BZ		BB		BZ		BB		BZ	
	COP	Head	COP	Head	COP	Head	COP	Head	COP	Head	COP	Head
Median	12.5	8.7	14.0	8.3	26.8	34.4	23.4	35.9	149	342	148	305
Lower quantile	11.5	8.0	11.7	7.9	18.6	25.8	19.2	27.7	104	242	93	258
Upper quantile	16.0	9.7	14.6	9.2	32.9	46.9	30.8	41.2	230	522	199	469
Minimum	9.2	6.4	9.5	6.8	14.2	19.8	15.7	17.5	54	174	47	159
Maximum	23.6	12.2	20.7	12.5	60.0	82.0	41.5	56.3	487	949	444	891
pp1	11.8	10.7	17.7	15.3	34.4	56.9	64.2	94.7	259	898	249	815
	15.4	13.1	14.0	11.5	37.6	62.1	46.8	75.7	287	893	535	1317
	14.1	12.0	13.1	11.4	49.4	71.9	58.2	109.5	309	1433	388	1505
pp2	12.9	15.3	13.4	9.4	25.8	54.2	18.4	41.4	231	2459	335	1049
	13.5	11.4	11.1	9.2	27.1	47.9	22.9	26.7	623	841	210	553
	20.9	11.7	12.8	10.8	46.1	50.1	28.8	76.7	873	1514	521	2506
pp3	18.8	11.7	19.2	12.8	31.5	47.3	54.2	50.7	453	971	1450	1687
	13.5	9.2	16.8	11.1	32.5	54.9	35.3	64.3	277	530	628	1282
	16.2	10.3	18.5	12.1	22.1	49.6	25.1	38.3	386	733	674	848

domain; this was obtained from the changes of the COP and the head in relation to the tests performed in the real environment. The values are presented in Table 3.

Table 3. Values of the amplitude of the first harmonic A1h and the A1h ratio calculated for the head in relation to A1h calculated for the COP for the BB and BZ tests

	A1h [mm]				Head_A1h / COP_A1h	
	BB		BZ			
	COP	Head	COP	Head	BB	BZ
Median	10.2	17.2	9.5	15.3	1.5	1.7
Lower quantile	8.8	13.9	7.4	12.8	1.4	1.5
Upper quantile	12.6	18.5	13.4	22.4	1.8	1.8
Minimum	4.9	6.8	4.2	7.6	0.7	1.3
Maximum	14.7	28.0	16.6	28.1	2.9	2.6
pp1	29.1	51.6	31.9	58.1	1.8	1.8
	15.3	32.7	25.6	48.7	2.1	1.9
	36.6	62.2	32.4	72.8	1.7	2.2
pp2	12.1	38.5	11.4	31.6	3.2	2.8
	11.9	41.0	13.9	15.9	3.4	1.1
	17.0	58.1	24.6	85.9	3.4	3.5
pp3	18.2	37.6	12.5	29.7	2.1	2.4
	22.5	43.7	14.5	38.3	1.9	2.6
	13.0	31.0	12.0	18.5	2.4	1.5

The values of V and EA in relation to the EO, EC, BB and BZ tests revealed statistically nonsignificant differences (in relation to *V*: ANOVA KW $p = 0.26$; in relation to the ellipse area (EA): ANOVA KW $p = 0.59$).

The second stage of analyses involved testing for differences between the calculated values of V, EA, D_{AD} (Table 2) and A1h (Table 3) in relation to the tests with (BZ) and without (BB) the signal warning disturbance. There were no statistically significant differences based on the Wilcoxon signed-rank test ($p \gg 0.05$).

The values of D_{AD} and A1h (Tables 2 and 3) were compared to examine differences between the displacement of the COP and the movement of the head. This analysis indicated the existence of significant differences when comparing D_{AD} and A1h for the group of healthy individuals ($p \ll 0.05$ for the Wilcoxon signed-rank test).

The third stage of analyses involved examining how the results for the individuals who qualified as more susceptible to the introduced disturbance could differ from those in the control group. The V values for pp1 and pp2 (all measurements) did not deviate from the medians obtained for the control group. The velocity was higher only for pp3. However, there were differences in the ellipse area (EA), with increased values for pp1 and pp3 for all measurements. There were increased values of EA for pp2 but only for the measurements in the virtual environment. The maximum and minimum values for the group of healthy individuals were single events, i.e., they appeared for a given person in one measurement, whereas values of the remaining measurements were similar to the median. As a result, the single high value data items could be treated as accidental losses of balance that were without diagnostic significance.

4. Discussion

Analyses needed to be completed in two directions to investigate how a simulated fall off stairs could trigger a loss of balance and whether an analysis of COP displacements and head movements could enable the identification of balance-related problems [34]. The first direction analyzed changes in parameters describing destabilization and postural compensation for the group of healthy individuals. Similarly to the research by Huweler [13], the analysis focused on head movements and COP displacements, and obtained displacement values in the AP direction. Related comparisons were completed in the real and virtual environments. To assess the effect of the visual stimulus (signal) on the COP displacements and head movements, it was necessary to analyze the average velocity, the ellipse area of prediction, and the range of movements after the disturbance. Similarly to the tests by Alpers [1] and Davis [8], the analysis in the frequency domain was performed to determine the amplitude of the first cyclic component of A1h.

The second direction compared results for individuals diagnosed as experiencing an impact of the introduced disturbance on balance with those for individuals who were healthy.

4.1. Analysis of the impact of the scenery disturbance on healthy participants

4.1.1. Comparison of the measurements in the real and virtual environments

The first stage of analyses included the comparison of the most frequently measured stabilometric parameters [6], namely, the area of ellipse (which made up 95% of the path of support) and the average velocity of the COP displacements. The comparison was performed on the measurements in the real environment with the participants having their eyes open and closed (Table 1), and in the virtual environment using the additional stimulus triggering the loss of balance (i.e., simulated fall off the stairs) (Table 2). The significant power of the test (>0.8) combined with statistically nonsignificant differences between the results of the measurements indicated that the introduced destabilizing stimulus did not affect the behavior of the test participants. It is possible that the classical analysis provided insufficient information regarding if, and how, the introduced visual stimulus affected changes in postural stability [16], [33]. The results and interpretative ambiguity should be unaffected by the small group size because effective statistical analysis in relation to small groups in similar postural stability-related tests has previously been well demonstrated by Keshner et al. [19]. The primary factor of importance might be that data interpreted in the aforesaid manner could be sensitive to disturbance (if any) in the form of losses of balance unrelated to the ability to maintain balance. This seems to be confirmed by large discrepancies in the values of such parameters in different research studies. For instance, in the tests performed by Błaszczyk et al. [2] on a group of approximately 21 year-olds (the use of force-plate posturography), the average velocity of the COP amounted to 9.8 mm/s (SD = 1.6) with eyes open and 12.2 mm/s (SD = 2.7) with eyes closed. In the tests performed by Skalska et al. [27], the average velocity of the COP amounted to 5.9 mm/s (SD = 2.5) with eyes open and 6.0 mm/s (SD = 2.2) with eyes closed. In previous tests by other authors, the average velocity of the COP amounted to 8.1 mm/s (SD = 0.8) with eyes open and 10.5 mm/s (SD = 2.3) with eyes closed. An even greater divergence could be observed for the ellipse area. In two independent tests performed by Błaszczyk et al. [2] and Rocchi et al. [26], the values of the ellipse area for persons aged 60–70, were 179.5 mm^2 (SD = 114.1) and 484 mm^2 (range of 197 mm^2 to 998 mm^2), respectively. Furthermore, previous tests on a group of individuals who were approximately 21 years of age provided different values, i.e., 154 mm^2 (SD = 94.3) with eyes open and 174 mm^2 (SD = 104.7) with eyes closed [15]. Such differences and the standard deviations of the COP-related ellipse area (for which the relative error often exceeded 50% of the average) could indicate that the analysis is insufficient (particularly under conditions of conflicting sensory stimuli). Therefore, it was necessary to extend the above analyses with parameters to enable a better and more comprehensive interpretation of findings.

4.1.2. Analysis of the impact of the warning stimulus

The use of the signal warning about the simulated fall off the stairs made it possible for a test participant to prepare for the situation [34]. This was done to determine if preparation for an expected disturbance would affect the behavior of test participants; to achieve this it was necessary to analyze parameters identified after the disturbance, i.e., D_{AD} and A1h (Tables 2 and 3). The HTC VIVE system displaying VR images was used to identify successive positions of the head (specifically, the VR headset in space). In this way, it was possible to extend analyses based on the COP measurements with analyses based on head movements.

There were no differences in the parameters with and without the use of the warning signal. Such differences are frequently noticeable in cases where actual stimuli are triggering the loss of balance [1], [5], and when the preparation (e.g., an impact) could lead to a delayed reaction. In terms of the tests, the disturbance in the form of a simulated fall off the stairs was purely visual and its effect was probably so strong that even the information about its appearance and previous experience of what it would look like did not change the response of participants.

In addition, the analysis of all obtained results indicated greater head movements. Taking into consideration the movement of the entire body as that of an upended pendulum, the above phenomenon was natural and confirmed by results from Wider [30].

The measurements made it possible to identify three individuals where there was a significant effect of the introduced disturbance on the ability to maintain balance. These three individuals were the subject of a separate case study.

4.2. Case study

During measurements, it was possible to single out three individuals (one based on the previous declaration and two based on the measurement results), where the values of selected parameters differed significantly from those of the remaining individuals. The recorded differences could indicate problems with maintaining balance when events affect the perception of the environment (e.g., being at height or an unexpected movement of the ground) [20], [34]. Particular attention should be paid to the fact that the greatest differences were demonstrated in parameters rarely used in such measurements (i.e., the cyclic components of the head movements determined using the fast Fourier transform).

4.2.1. Analysis of average velocity and the ellipse area of prediction

There were no clear differences between the group of healthy individuals and the three diagnosed with increased susceptibility to the introduced disturbance when examining the average velocity of the COP and the head (Table 2) (for measurements taken in the real environment). Although these parameters for the three individuals were higher than the median for the group, they were lower than the maximum values for the group. Thus, the parameters did not explicitly differentiate those individuals who were strongly affected by visual disturbance; this indicated that further analyses were needed.

Differences were noticeable when viewing the COP-related ellipse area (Table 2). All of these values for the three individuals (during measurements in the virtual environment) were higher than the upper quantile. In addition, some of the measured values exceeded the maximum values for the group (for pp1 – one measurement, and for pp2 and pp3 – three measurements). Furthermore, the ellipse area values (which were identified for the head movements) for the three cases (Table 2) were higher than the upper quantile of the reference group. In half of the cases, these values were also higher than the maximum values for the healthy participants. The increased values of the ellipse area, particularly those obtained with the head movements, could indicate that a given participant found it difficult to maintain balance after experiencing the disturbance. However, such differences were only observed for some measurements, which could imply a momentary loss of balance.

The range of the COP displacements and head movements (Table 2) did not unequivocally indicate the scale of the disturbance effect on the three individuals. Only pp1 revealed increased values of the analyzed parameter. In half of the cases, the values were higher than the maximum values for the group. For the remaining cases, the values were higher than the upper quantile. For pp2 and pp3, the values varied from similar to the median to sporadically higher than the maximum for the group.

These ambiguities could limit the usefulness of such measurements in diagnosing problems with maintaining balance. For this reason, it is necessary to find parameters which could provide the most repeatable results.

4.2.2. Analysis of the first harmonic – balance maintaining strategy

The frequency analysis of the tests concerning balance made it possible to break down the signal composed of changes in the positions of the COP and those of the head into successive cyclic components, giving the frequency and amplitude of such movements [15], [16], [19]. The use of the fast Fourier transform in the tests revealed that the application of the destabilizing stimulus (in the form of a simulated fall off the stairs) triggered the appearance of the cyclic component with the highest amplitude of 0.1 Hz to 0.2 Hz. The analysis of this for the reference group and pp1, pp2, and pp3 (Table 3) did not reveal differences between the tests with and without the warning stimulus. However, there were significant differences for the three individuals (i.e., pp1, pp2, and pp3), compared to the remaining participants. These differences were visible early when comparing the values of the amplitude of the first harmonic obtained with the COP displacements, yet the greatest differences were observed with this parameter in relation to the head movements. In the second case, only two values (i.e., one for pp2 and one for pp3) were lower than the upper quantile of the group. The remaining values were between 1.3 and 3.8 times higher than the upper quantile and between 1.05 and 3.1 times higher than the maximum values for the rest of the group. Such repeatability of increased amplitude of the harmonic peak was not observed for any other test participant. Such increased values obtained for other persons were sporadic results, obtained in single measurements for a given person.

The above results indicate that, when analyzing the effect of disturbances due to virtual reality and, probably in other balance-related tests, it is necessary to take the COP displacements (which is a certain standard) and movements of other parts of the body (e.g., head – as in the case of this study) into consideration. Even when the head movements are taken into account, an ordinary analysis in the time domain could be insufficient for detecting differences among test subjects. For the tests discussed in this article, only separate analyses of individual cyclic components indicated differences that distinguished the three individuals from the entire group.

Furthermore, the determination of the first harmonic indicated the strategy adopted by individual participants to maintain their balance. The proportion of the first harmonic amplitude for the head and the COP (Table 3) indicated whether a given person balanced using their entire (stiffened) body (value of the ratio close to 1) or whether head movements dominated over the COP displacements. The latter case, as could be surmised (because it was not directly measured) involved a larger range of trunk movements combined with the simultaneous flexion/extension of the hip joint and dorsal/plantar flexion of the ankle. The appropriate synchronization of movements causes an increased range of trunk movements and a slight range in the COP displacements (all in the AP direction). The tests revealed that the aforementioned strategy dominated in the three individuals as indicated by increased parameter values. This implies that individuals having difficulty maintaining balance will apply the above strategy of balancing their body in virtually disturbed (i.e., moving) surroundings. This also explains slight differences in parameters identified on the basis of the successive COP displacements. The above conclusion could be important in diagnosing problems with maintaining balance, but requires more tests and verification.

The determination of a coefficient describing the strategy for maintaining balance should not only include parameters determined in the time domain (e.g., ranges of the COP displacements and head movements), but should primarily include the harmonic of the FFT that is characterized by the highest amplitude. Such an analysis could help filter out slight movements, which do not necessarily determine the global movement strategy.

5. Conclusions

The application of the VR technology along with the creation of visual stimuli aimed to trigger the loss of balance could help diagnose balance-related problems and extend tests of balance involving standing with one's eyes open and closed. The VR-aided simulation of phenomena, which could occur in reality, enables the activation of mechanisms for achieving an appropriate posture following exposure to disturbances. The proper understanding of these underlying mechanisms could help in the development of systems and methodology for detecting balance-related problems. Such problems are manifested by an improper reaction to the upsetting of the balance of the stabile posture; these may be undetectable during tests in the real environment, which is why VR technology can be helpful.

The results revealed that measurements under conditions of conflicting sensory stimuli required an extension of the traditional approach for a more comprehensive analysis of results. The parameters most commonly analyzed when assessing the ability to maintain balance do not provide a full answer as to how the stimuli introduced to upset balance affects a given person. Thus, this study recommends the use of analyses in the frequency domain to provide a more comprehensive view of how upsetting the balance impacts individuals. The tests also revealed that measurements of the successive COP positions (currently the most frequent method of assessing the ability to maintain balance) could prove insufficient in analyzing balance. Additional measurements with head movements extended the possibilities of interpreting results obtained in related balance tests.

The amplitude of the first harmonic, particularly with respect to the head movements, most repeatedly differentiated the individuals with the highest susceptibility to the introduced disturbance. It should be emphasized that such results do not necessarily indicate the existence of health disorders; however, the increased susceptibility to certain forms of disturbance could translate into unexpected behavior during work at heights or when playing sports requiring fast movements of the head.

Conflict of interest

The authors declare no conflict of interest. The authors declare that all authors were fully involved in the study and the preparation of the manuscript and that the material within has not been and will not be submitted for publication elsewhere.

Acknowledgements

Publication supported as part of program "Inicjatywa Doskonałości – Uczelnia Badawcza" implemented at Silesian University of Technology, year 2020/2021.

References

[1] ALPERS G.W., ADOLPH D., *Exposure to heights in a theme park: fear, dizziness, and body sway*, Journal of Anxiety Disorders, 2008, 22, 591–601

[2] BŁASZCZYK J.W., ORAWIEC R., DUDA-KŁODOWSKA D., OPALA G., *Assessment of postural instability in patients with Parkinson's disease*, Experimental Brain Research, 2007, 183, 170–114.

[3] BŁAŻKIEWICZ M., DOWCIP A., *Comparison of sensitivity coefficients for joint angle trajectory between normal and pathological gait*, Acta of Bioengineering and Biomechanics, 2012, 14 (1), 83–91.

[4] BUCHNER D.M., LARSON E.B., *Falls and fractures in patients with Alzheimer-type dementia*, JAMA, 1987, 257, 1492–1495.

[5] CHANDER H., KODITHUWAKKU ARACHCHIGE S.N.K., HILL C.M., TURNER A.J., DEB S., SHOJAEI A., HUDSON C., KNIGHT A.C., CARRUTH D.W., *Virtual Reality-Induced Visual Perturbations Impact Postural Control System Behavior*, Behavioral Sciences, 2019, 9 (11), 113.

[6] CLEWORTH T.W., CHUA R., INGLIS J.T., CARPENTER M.G., *Influence of virtual height exposure on postural reactions to support surface translations*, Gait & Posture, 2016, 47, 96–102.

[7] CRIPPS A.E., LIVINGSTON S.C., DESANTIS B., *The Test-Retest Reliability and Minimal Detectable Change of the Sensory Organization Test and Head-Shake Sensory Organization Test*, Journal of Sports Medicine and Allied Health Sciences: Official Journal of the Ohio Athletic Trainers Association, 2016, 2 (2).

[8] DAVIS J.R., CAMPBELL A.D., ADKIN A.L., CARPENTER M.G., *The relationship between fear of falling and human postural control*, Gait and Posture, 2009, 29, 275–279.

[9] DOKKA K., KENYON R.V., KESHNER E.A., *Influence of visual scene velocity on segmental kinematics during stance*, Gait Posture, 2009, 30, 211–216.

[10] DUDA S., GEMBALCZYK G., JURECZKO P., *The effect of body weight unloading on kinematic gait parameters during treadmill walking*, Engineering Mechanics, 2017, 282–285.

[11] ETMAN A., WIJLHUIZEN G.J., VAN HEUVELEN M.J., CHORUS A., HOPMAN-ROCK M., *Falls incidence underestimates the risk of fall-related injuries in older age groups: a comparison with the FARE (Falls Risk by Exposure)*, Age Ageing, 2012, 41, 190–195.

[12] GAGO M.F., YELSHYNA D., BICHO E., SILVA H.D., ROCHA L., RODRIGUES M.L., SOUSA N., *Compensatory Postural Adjustments in an Oculus Virtual Reality Environment and the Risk of Falling in Alzheimer's Disease*, Dementia and Geriatric Cognitive Disorders Extra, 2016, 6 (2), 252–6740.

[13] HUWELER R., KANDIL F.I., ALPERS G.W., GERLACH A.L., *The impact of visual flow stimulation on anxiety, dizziness, and body sway in individuals with and without fear of heights*, Behaviour Research and Therapy, 2009, 47, 345–352.

[14] JURAS G., BRACHMAN A., MARSZAŁEK W., KAMIENIARZ A., MICHALSKA J., PAWŁOWSKI M., SŁOMKA K., *Using Virtual Reality To Improve Postural Stability In Elderly Women*, Medicine and Science in Sports and Exercise, 2020, 52 (17), 553–554.

[15] JURKOJĆ J., *Balance disturbances coefficient as a new value to assess ability to maintain balance on the basis of FFT curves*, Acta of Bioengineering and Biomechanics, 2018, 20 (1), 143–151.

[16] JURKOJĆ J., WODARSKI P., MICHNIK R., MARSZAŁEK W., SŁOMKA K. J., GZIK M., *The Use of Frequency Analysis as a Complementary and Explanatory Element for Time Domain Analysis in Measurements of the Ability to Maintain Balance*, Journal of Human Kinetics, 2021, 76, 117–129.

[17] KANNUS P., SIEVÄNEN H., PALVANEN M., JÄRVINEN T., PARKKARI J., *Prevention of falls and consequent injuries in elderly people*, Lancet, 2005, 366, 1885–1893.

[18] KENYON R.V., ELLIS S.R., *Vision, perception, and object manipulation in virtual environments*, [in:] P.L.T. Weiss, E.A. Keshner, M.F. Levin (Eds.), *Virtual Reality for Physical and Motor Rehabilitation, Virtual Reality Technologies for Health and Clinical Applications*, Springer, 2014, 1, 47–70.

[19] KESHNER E.A., KENYON R.V., DHAHER Y., *Postural Research and Rehabilitation in an Immersive Virtual Environment*, Proceedings of the 26th Annual International Conference of the IEEE EMBS San Francisco, 2004.

[20] KOBAYASHI K., FUSHIKI H., ASAI M., WATANABE Y., *Head and body sway in response to vertical visual stimulation*, Acta Otolaryngologica, 2005, 125, 858–862.

[21] MARTINEZ-MENDEZ R., SEKINE M., TAMURA T., *Postural sway parameters using a triaxial accelerometer: comparing elderly and young healthy adults*, Computer Methods in Biomechanics and Biomedical Engineering, 2012, 15, 899–910.

[22] MICHALSKA J., KAMIENIARZ A., BRACHMAN A., MARSZAŁEK W., CHOLEWA J., JURAS G., SŁOMKA K.J., *Fall-related measures in elderly individuals and Parkinson's disease subjects*, PLOS ONE, 2020, 15 (8), e0236886.

[23] NADHIM E.A., HON C., XIA B., STEWART I., FANG D., *Falls from height in the construction industry: a critical review of the scientific literature*, International Journal of Environmental Research and Public Health, 2016, 13 (7), 638.

[24] PALMERINI L., ROCCHI L., MELLONE S., VALZANIA F., CHIARI L., *Feature selection for accelerometer-based posture analysis in Parkinson's disease*, IEEE Transaction of Information Technology in Biomedicine, 2011, 15, 481–490.

[25] POLECHOŃSKI J., NAWROCKA A., WODARSKI P., TOMIK R., *Applicability of Smartphone for Dynamic Postural Stability Evaluation*, BioMed Research International, 2019, 2019, 1–6.

[26] ROCCHI L., CHIARI L., HORAK F.B., *Effects of deep brain stimulation and levodopa on postural sway in Parkinson's disease*, Journal of Neurology, Neurosurgery and Psychiatry, 2002, 73 (3), 267–274.

[27] SKALSKA A., OCETKIEWICZ T., ŻAK M., GRODZICKI T., *Influence of Age on Postural Control Parameters Measured with a Balance Platform*, Borgis-New Medicine, 2004, 1, 112–116.

[28] STOFFREGEN T.A., PAGULAYAN R.J., BARDY B.G., HETTINGER L.J., *Modulating postural control to facilitate visual performance*, Hum. Movement Science, 2000, 19, 203–220.

[29] WATANABE T., SAITO H., KOIKE E., NITTA K., *A preliminary test of measurement of joint angles and stride length with wireless inertial sensors for wearable gait evaluation system*. Computational Intelligence and Neuroscience, 2011, 975193.

[30] WIDER C., MITRA S., ANDREWS M., BOULTON H., *Age-related differences in postural adjustments during limb movement and motor imagery in young and older adults*, Experimental Brain Research, 2020, 238 (4), 771–787.

[31] WINIARSKI S., CZAMARA A., *Evaluation of gait kinematics and symmetry during the first two stages of physiotherapy after anterior cruciate ligament reconstruction*, Acta Bioeng. Biomech., 2012, 14 (2), 91–100.

[32] WODARSKI P., JURKOJĆ J., BIENIEK A., CHRZAN M., MICHNIK R., POLECHOŃSKI J., GZIK M., *The Analysis of the Influence of Virtual Reality on Parameters of Gait on a Treadmill According to Adjusted and Non-adjusted Pace of the Visual Scenery*, 7th International Conference on Information Technology in Biomedicine, ITIB 2019, 1011, 543–553.

[33] WODARSKI P., JURKOJĆ J., POLECHOŃSKI J., BIENIEK A., CHRZAN M., MICHNIK R., GZIK M., *Assessment of gait stability and preferred walking speed in virtual reality*, Acta Bioeng. Biomech., 2020, 22 (1), 127–134.

[34] YELSHYNA D., GAGO M.F., BICHO E., FERNANDES V., GAGO N.F., COSTA L., SILVA H., RODRIGUES M.L., ROCHA L., SOUSA N., *Compensatory postural adjustments in Parkinson's disease assessed via a virtual reality environment*, Behavioural Brain Research, 2006, 296, 384–392.