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Balance disturbances coefficient as a new value to assess ability to maintain balance on the basis of FFT curves

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Purpose: The aim of this study was to formulate a new balance disturbances coefficient enabling objective balance assessment on the basis of fast Fourier transform curves. The article presents the method of coefficient calculation and possible ways of its interpretation. *Methods:* 11 healthy participants took part in the experiment. There were four measurements: two in real environment with eyes open and eyes closed as well as two in virtual environment with scenery (surroundings) oscillating with frequency 0.7 Hz and 1.4 Hz. Scenery was displayed by means of the Oculus Rift system, whereas position of centre of pressure was measured with the use of Zebris FDM-S platform. Obtained centre of pressure positions were used to calculate fast Fourier transform, and then balance disturbances coefficient. *Results:* Comparisons of coefficient values obtained for the whole group and two selected participants were presented in order to explain how to interpret and use the coefficient. For better explanation of coefficient interpretation the most popular time domain stabilometric quantities and fast Fourier transform curves were presented as well. *Conclusions:* The balance disturbances coefficient makes it possible to quantitatively and objectively determine, on the basis of fast Fourier transform curves, the influence of the oscillating scenery on the tested person as well as show how the overall equilibrium of that person was disturbed.

Key words: *balance, stabilography, fast Fourier transform, coefficient*

1. Introduction

The ability to maintain balance by a human being is one of the fundamental skills enabling an active lifestyle and performing everyday activities [15]. This ability is defined as a skill to maintaining certain position of the body without the help of another person and to regain this position after the external stimulus, which could potentially cause a fall [2]. Balance disorders can cause falls, fear of walking or even lead to complete immobility of a person [2], [3], [14]. The reason for losing the ability to properly maintain balance may have neurological background (e.g., multiple sclerosis, stroke, Parkinson's disease, cerebral palsy), can occur after some injuries and operations or appear as a result of obesity and advanced age [3], [7], [9]. Therefore, it is important to conduct research that enable a full understanding of mechanisms associated with the process of maintaining balance and result with new diagnostic and rehabilitation methods leading to the quickest restoration of this skill.

Currently, the basic diagnostic methods for balance problems are based on measurements successive positions of the centre of pressure (COP) under static conditions with eyes open and closed [8], [16], [21]. Although this methodology is simple and very useful, it can be insufficient in the cases when selective analysis of the functioning of individual senses responsible for maintaining the balance is required [4], [17]. Such assessments need measurements con-

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ducted in conditions where stimuli reaching selected senses is eliminated selected stimuli is modified so that the information which reach individual senses are in conflict, for example, immobile floor and moving surroundings. Such measurements are called measurements in sensory conflict conditions. The second method also enables to determine how the balance control system handles with contradictory information [3], [6], [25]. The use of virtual reality technology, especially in its immersive version, is one of the ways of doing this type of measurements. Research on such use of virtual sceneries was conducted, among others, by Keshner et al. [13], [24], Cunningham et al. [5] as well as by the author of this article [10], [18], [19].

The results obtained show that the measurements carried out in this manner provide a lot of valuable information concerning the ability to maintain balance. The also proved that the standard analyses of test results based on quantities calculated in time domain (e.g., the path length of the COP or an ellipse area containing 95% of the COP positions) can be insufficient or even lead to incorrect interpretation of measurement results. Interpretation of quantities determined in time domain is based primarily on assumed correlation between the increase in value of these quantities and the deterioration of the ability to maintain balance. In the case of measurements performed in sensory conflict conditions, such assumption may not be true. Oscillating environment, as in the case of studies described in this paper, may affect the increase in value of time domain quantities not only in people with problems with maintaining balance, but also in healthy people. This is due to the fact that the moving scenery is treated as a potential risk of fall and activates adequate mechanisms to counteract it – the body begins to perform an additional, oscillating movement that is in the opposite phase to the movement of the environment. This causes the increase of value of quantities determined in time domain both in healthy people and in people with existing problems with maintaining balance. This fact makes the analysis very difficult, because it seems to be impossible to state whether the value of quantity is correct or when it indicates potential problems. Therefore, development of analysis methods conducted in frequency domain is crucial.

Signal analysis in frequency domain is mainly carried out to collect information about system which generates signals. For this purpose, the fast Fourier transform (FFT) is one of the most often used. The obtained FFT curves enable identification of cyclical components of the signal together with the corresponding frequencies. Although this method used in stabilometric measurements conducted in sensory conflict conditions increase diagnostic possibilities, it is still not used in daily practice. There are two main reasons for this. The first one results from the fact that correct interpretation of FFT curves needs at least basic knowledge about the fast Fourier transform, which is a quite complicated method based on sophisticated mathematics. The second one is lack of coefficients based on FFT results or similar to other coefficients currently used in medical diagnosis process [11], [12], [20], [22], [23], which change complicated FFT curves into one number describing patient's state.

Therefore, the aim of this research was to formulate a new balance disturbances coefficient enabling objective balance assessment on the basis of signal analysis methods in frequency domain.

2. Methods

2.1. Method of calculation and interpretation of a balance disturbances coefficient

In order to enable quantitative, based on frequency analysis, assessment of the ability to maintain balance a new balance, disturbances coefficient was developed. It is dedicated primarily to the research conducted in sensory conflict conditions performed by means of oscillating virtual sceneries, but it can also be used in standard stabilographic studies. This coefficient is primarily aimed at:

- enabling an objective, quantitative analysis of the ability to maintain balance on the basis of the FFT curves,
- enabling the analysis of the ability to maintain balance during research conducted in sensory conflict conditions realized by means of oscillating scenery displayed with the use of devices for three-dimensional image projection,
- eliminating the potential incorrect interpretations of the results obtained in time domain for measurements conducted in sensory conflict conditions realized by means of moving scenery,
- enabling independent interpretation of the results calculated in frequency domain and taking into account as well as not taking into account cyclic component of COP movement realized with frequency equal to frequency of oscillating virtual scenery.

2.1.1. General assumptions for calculation of balance disturbances coefficient

The use of frequency analysis enables the identification of cyclic components present in the signal. The existence of components is determined on the basis of the successive peaks (local maxima) on the FFT curve. In the case of stabilographic tests, individual values describing successive peaks can be interpreted as follows:

- the higher value of the frequency of the cyclic component corresponds to higher value of COP velocity,
- the higher value of amplitude corresponds to higher value of COP path and velocity.

On this basis, it can be stated that the greater the values of frequency and amplitude, the faster the movement of COP. This, in turn, indicates that process of standing is more disturbed. The correct identification and interpretation of the following FFT peaks can support an assessment of ability to maintain balance. This assumption is a basis for a new coefficient.

2.1.2. Method of calculation of balance disturbances coefficient

Based on the assumptions made, the algorithm for calculating the coefficient was developed. At first, successive peaks (maxima) are detected. Then, for the found maxima, the coefficient is calculated according to the following formula:

$$W_r = \sum_{n=1}^{N} A_n^2 f_n \qquad (1)$$

where:

W_r – balance disturbances coefficient,

A_n – value of amplitude of the n^{th} peak,

f_n – value of frequency of the n^{th} peak,

N – total number of detected peaks.

During calculations presented in the next chapter, additional assumptions were made:

- detection of the following peaks was limited to frequencies between 0.15 Hz and 2.0 Hz,
- a peak was taken into account provided that there were no other peaks of greater value of amplitude before and after this peak in a range of ±0.1 Hz,
- a peak was taken into account provided that the value of amplitude was equal or greater than 0.5.

The coefficient was determined in two variants:

- the peak near frequency equal to frequency of scenery oscillation was taken into account,
- the peak near frequency equal to frequency of scenery oscillation was not taken into account.

Two variants of the coefficient enable differentiation between the COP motion realized with the frequency of scenery and movements carried out with other frequencies.

2.2. Exemplary interpretation of a balance disturbances coefficient

The value of the balance disturbances coefficient depends on the square values of amplitudes of the following peaks and their frequencies. Both greater value of frequency and greater value of amplitude of a peak point to greater value of COP velocity and, in consequence, less stabile process of standing. Hence, the assumption can be made that the increasing value of the coefficient will indicate growing problems with the balance.

Two variants of coefficient – with and without the peak formed near the frequency of scenery movements, make the analysis more detailed. The value obtained after calculations taking into account that peak shows how the given external disturbance (oscillating scenery) completely affected the behaviour of the examined person. The value calculated without this peak shows how this disturbance influenced the process of balance maintaining, or, in other words, how big were the movements other than this performed at the frequency of scenery movement.

The first value of the coefficient seems to be more important in the case of research on influence of virtual scenery motion on participant behaviour, while the second can be used in medical applications serving as a diagnostic indicator of imbalances.

The exemplary interpretation of the balance disturbances coefficient was carried out for two subjects individually and in reference to results obtained for the group of 11 healty people.

2.2.1. Participants

A group of 11 participants (7 females and 4 males) of a mean weight 64 kg, a mean height 171.3 cm and a mean age 22.4 took part in measurements. All selected participants were healthy, had no problems with balance maintaining and were not obese (BMI less than 30).

This study was previously approved by the Ethics in Research Committee of the Academy of Physical Education in Katowice (protocol number 11/2015).

2.2.2. Measurement position

All measurements of COP positions were conducted with the use of Zebris FDM-S platform. Platform's software enables export of subsequent COP coordinates. These coordinates were used in FFT calculations.

The 3D projection of scenery was carried out by means of the Oculus Rift system. The scenery was prepared in the Unity environment and was designed as a furnished room with objects seen in a distance less than 3 meters.

During measurements the hole scenery was oscillating. The motion was programed as a harmonic movement conducted with the following parameters:

- translational motion along a participant's sagittal axis according to the following equation:

$$y = A_y \sin(2\pi f_t t) \tag{2}$$

where:

f_t – frequency of scenery translational motion [Hz],
A_y – amplitude of scenery motion [cm],
t – time [s];

- rotational motion around a participant's transversal axis according to the following equation:

$$\varphi = A_\varphi \sin(2\pi f_r t) \tag{3}$$

where:

f_r – frequency of scenery rotational motion [Hz],
A_φ – amplitude of scenery motion [deg],
t – time [s].

The following values of the parameters were assumed:

- $A_y = 15$ [cm],
- $A_\varphi = 1$ [deg],
- $f_r = 0.5 \cdot f_t$ [Hz],
- $f_t = 0.7$ [Hz] and $f_t = 1.4$ [Hz] – depending on the measurement.

2.2.3. Method of measurements

Each participant took part in four measurements:

- real environment, eyes open,
- real environment, eyes closed,
- virtual environment, frequency of scenery motion equal to 0.7 Hz,
- virtual environment, frequency of scenery motion equal to 1.4 Hz.

Before the measurement each participant was informed about the study and could become familiar with the virtual scenery. Then, the subject had to stand barefoot on the measuring platform in an upright position, with feet set at hip level. During the measurement it was necessary to stand motionless with arms crossed on the chest, focusing on the designated point. Each measurement lasted 50 seconds. In the measurements carried out in virtual environment the scenery started to oscillate in the 10th second of measurement and lasted 30 seconds. In analyses a 30-second sections of the measurement were taken into account:

- real environment – middle part of the measurement,
- virtual environment – section recorded during scenery motion.

After measurements, the coordinates of COP positions were exported and used to calculate fast Fourier transform. Next, FFT results were used to determine values of balance disturbances coefficient.

3. Results

Figures 1–4 present FFT curves obtained for two chosen participants during measurements in real (eyes open and closed) and virtual (scenery motion with frequency equal to 0.7 Hz and 1.4 Hz) environment. FFT curves are presented for frequencies between 0 and 2 Hz, because for higher values of frequencies no peaks were observed.

All values of calculated balance disturbances coefficient are presented in Tables 1 and 2. Mean values of the coefficient obtained for the whole group of 11 participants are presented in the Table 1, whereas Table 2 presents values calculated for two selected persons. Table 3 presents values of quantities calculated in time domain, which are the most commonly used quantities in balance assessment process: mean velocity of COP and ellipse area, which were obtained for the same group of participants.

According to assumptions concerning the way of calculation of two variants of coefficient, values of coefficient for the presented, exemplary results were calculated:

- taking into account all peaks,
- excluding peak near 0.7 Hz,
- excluding peak near 1.4 Hz.

All these results are presented in Tables 1 and 2 but analysis and discussion were conducted based on the following results:

- the coefficient calculated taking into account all peaks – all measurements in real and virtual environment,
- the coefficient calculated without peak near 0.7 Hz – measurement in virtual environment with scenery oscillating with frequency equal to 0.7 Hz,
- the coefficient calculated without peak near 1.4 Hz – measurement in virtual environment with scenery oscillating with frequency equal to 1.4 Hz.

Values not taken into account in analyses are shadowed in Tables 1 and 2.

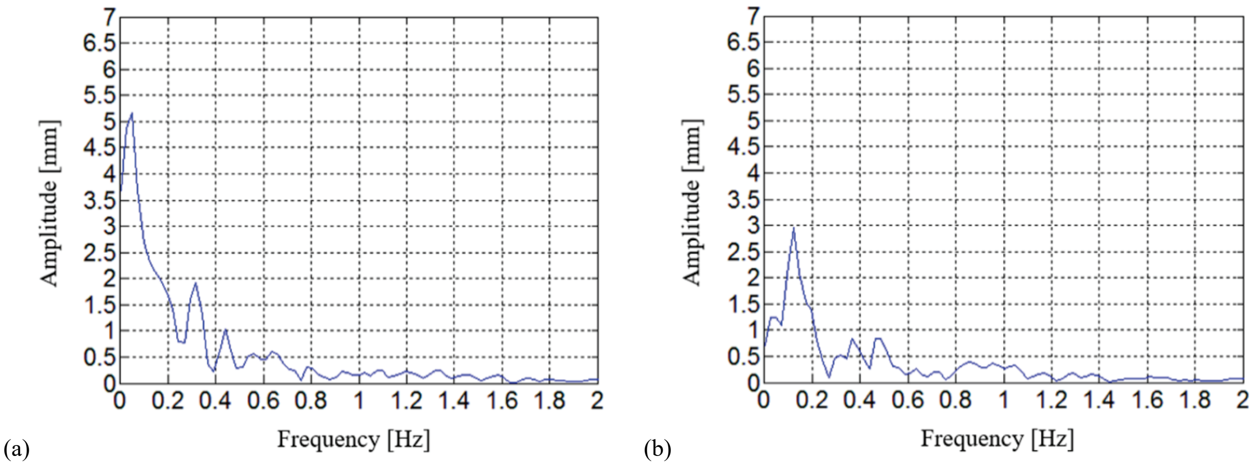


Fig. 1. FFT curves obtained for participant 1 during (a) eyes open test, (b) eyes closed test. Results were calculated in sagittal plane

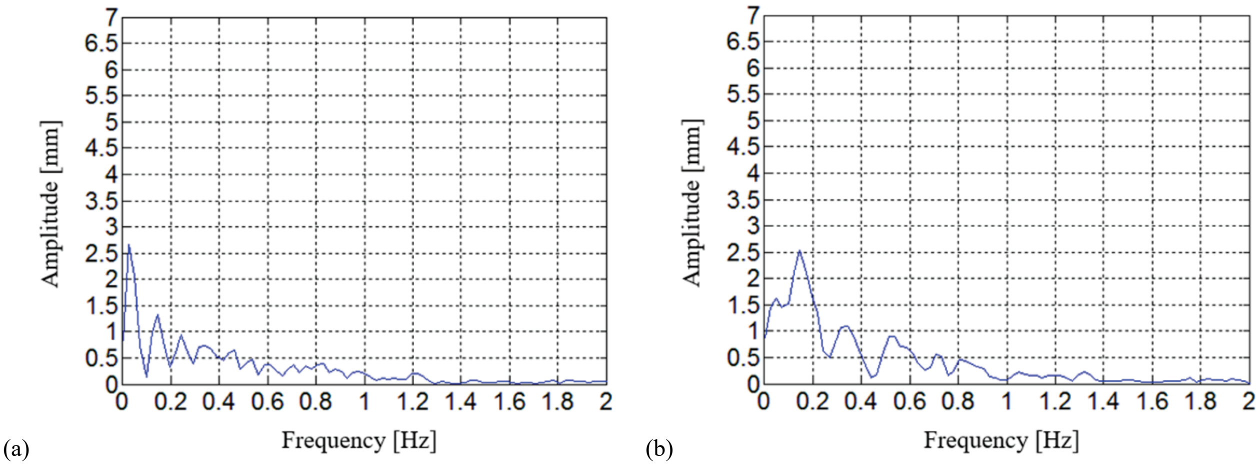


Fig. 2. FFT curves obtained for participant 2 during (a) eyes open test, (b) eyes closed test. Results were calculated in sagittal plane

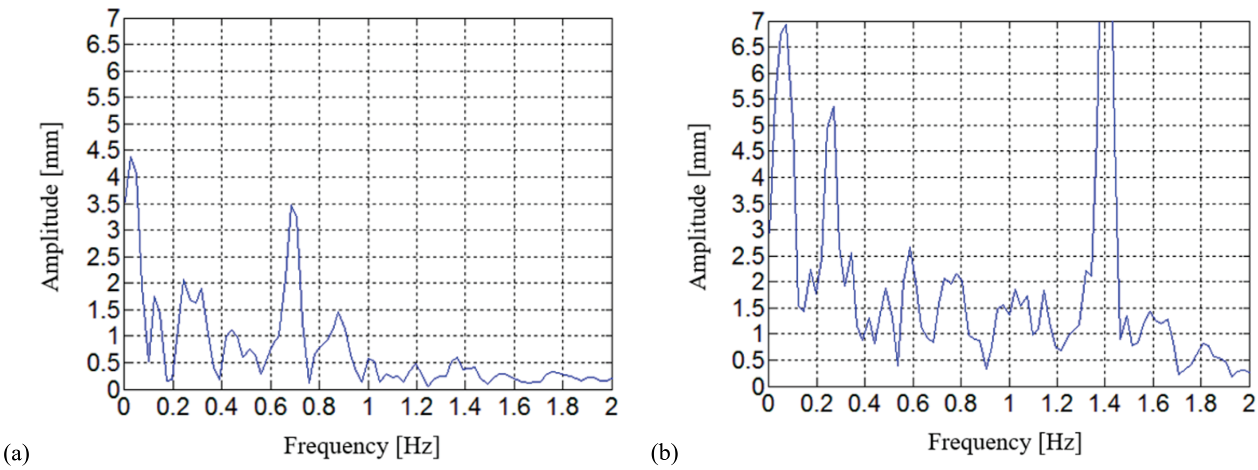
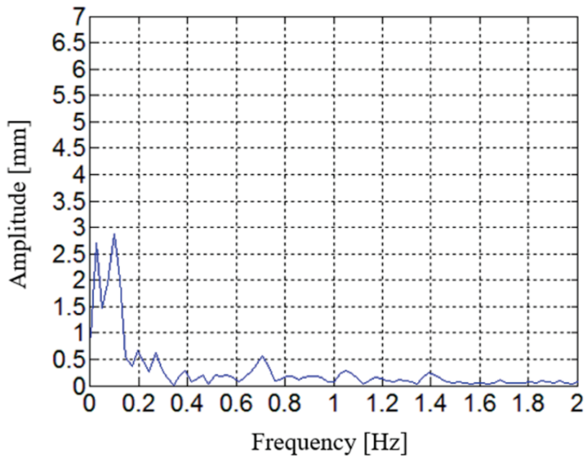
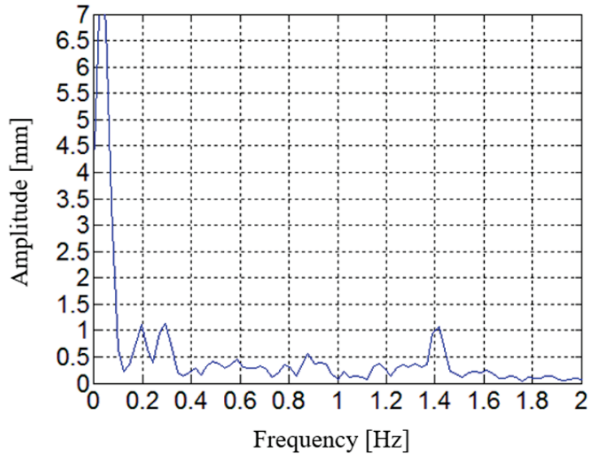


Fig. 3. FFT curves obtained for participant 1 during (a) test with scenery oscillating with frequency 0.7 Hz, (b) test with scenery oscillating with frequency 1.4 Hz. Results were calculated in sagittal plane



(a)



(b)

Fig. 4. FFT curves obtained for participant 2 during (a) test with scenery oscillating with frequency 0.7 Hz, (b) test with scenery oscillating with frequency 1.4 Hz. Results were calculated in sagittal plane

Table 1. Mean values of balance disturbances coefficient calculated for all participants. eo – eyes open, ec – eyes closed. Results were calculated in sagittal plane

Measurement	Mean values (SD) of the coefficient	Mean values (SD) of the coefficient calculated without the peak near 0.7 Hz	Mean values (SD) of the coefficient calculated without the peak near 1.4 Hz
eo	0.91 (0.60)	0.86 (0.59)	0.91 (0.61)
ec	2.10 (1.59)	1.91 (1.31)	2.11 (1.58)
0.7 Hz	19.10 (20.70)	5.30 (4.70)	18.10 (19.30)
1.4 Hz	37.40 (52.30)	37.40 (52.30)	8.90 (10.00)

Table 2. Results of balance disturbances coefficient obtained for two selected participants. eo – eyes open, ec – eyes closed. Results were calculated in sagittal plane

Measurement	Values of the coefficient		Values of the coefficient calculated without the peak near 0.7 Hz		Values of the coefficient calculated without the peak near 1.4 Hz	
	Participant 1	Participant 2	Participant 1	Participant 2	Participant 1	Participant 2
eo	1.97	0.21	1.97	0.21	1.97	0.21
ec	0.99	1.36	0.99	1.36	0.99	1.36
0.7 Hz	12.12	0.31	3.93	0.09	11.63	0.31
1.4 Hz	186.50	2.29	186.50	2.29	27.33	0.66

Table 3. Results of time domain quantities obtained for two selected participants as well as mean value determined for the whole group of 11 participants. eo – eyes open, ec – eyes closed

Measurement	Mean velocity of COP [mm/s]			Ellipse area [mm^2]		
	Participant 1	Participant 2	Mean value for the whole group (SD)	Participant 1	Participant 2	Mean value for the whole group (SD)
eo	7.6	8.9	8.1 (0.8)	233.9	74.5	154.5 (94.3)
ec	8.0	10.2	10.5 (2.3)	124.7	92.6	174.7 (104.7)
0.7 Hz	34.8	7.9	22.1 (11.7)	952.0	87.9	499.1 (338.5)
1.4 Hz	79.9	11.5	26.9 (19.0)	1529.9	367.7	619.9 (491.6)

4. Discussion

4.1. Analysis of time domain quantities

Table 3 presents values of two selected quantities analysed in time domain. According to generally accepted standard the increased values of these quantities indicate potential problem with the ability to maintain balance [7]. In the case of analysed quantities (mean velocity and ellipse area) a slight increase of values can be observed after closing eyes (29% in the case of mean velocity and 13% in the case of ellipse area in relation to the eyes open results) while the values obtained after the introduction of virtual disturbances are much higher. Compared to the eyes open test, the increase of mean velocity was about 172% for frequency 0.7 Hz and 232% for 1.4 Hz and the increase of ellipse area was about 223% for 0.7 Hz and 301% for 1.4 Hz. Additionally it can be observed that implementation of any virtual disturbances is followed by the increase of value of standard deviation, what can be the evidence of the growth of human diversity observed by Cousin et al. [6] and Akiduki et al. [1].

4.2. Analysis of FFT curves

The use of time domain analysis based on correlation between higher values of measured quantity and worse ability to maintain balance is true in tests carried out without any external disturbances. Implementation of, e.g., moving scenery makes this correlation untrue. Figures 1–4 present FFT curves obtained for tested participants. One can notice visible peaks near frequencies equal to frequencies of sceneries oscillation (Figs. 3 and 4), which do not exist in curves obtained in real environment (Figs. 1 and 2). That means, that there is additional component of motion. Assuming that this component, corresponding to body oscillation carried out with frequency of scenery oscillation, is a natural reaction protecting against a potential fall, increase of values of time domain quantities is also natural and do not correlate with problems with maintaining balance.

Analysis of FFT curves makes it possible to draw another, more interesting conclusion. The peak near frequency equal to scenery oscillation is not the only peak appearing in FFT curves. Analysing results obtained for the participant 1 (Fig. 3) one can notice plenty of other peaks. These peaks indicate that there are more cyclic components in. Moreover, these additional peaks are not characteristic for everybody (e.g., Fig. 4 – participant 2). These conclusions can suggest that these additional components – peaks – are more interesting in terms of medical diagnosis, because they can correlate with problems with maintaining balance. More such components, especially performed at higher frequencies, correspond to quick movements of the body performed by a person trying not to fall. Based on conclusions drawn it seems that frequency domain analysis, should complement time domain analysis especially in tests carried out in sensory conflict conditions. But visual FFT curves analyses can be rather difficult and, above all, not objective. Therefore, a coefficient enabling quantitative analyses was elaborated within the frame of this work.

4.3. Balance disturbances coefficient analysis

Mean values of the coefficient obtained for a group of participants (Table 1) show that the influence of oscillating virtual scenery is visible for both frequencies of scenery oscillations – all values are higher in comparison with results obtained in real environment.

Results obtained for participants 1 and 2 (Table 2) show that the influence of virtual, moving scenery can be very different for individual people. According to these results, the influence of oscillating, virtual scenery on participant 2 is negligible. Values of all results, both in time and frequency domain, obtained in virtual environment are similar to those obtained in real environment.

Results obtained for participant 1 are much more interesting. In this case, one can notice much higher values obtained in virtual environment, compared to results obtained for that person in real environment. That proves the presence of the influence of oscillating scenery. Values of coefficients of that person (Table 2), compared with the results obtained for the whole group (Table 1), show that scenery oscillation performed with frequency 0.7 Hz influenced participant 1 similarly to the whole group (value for participant 1 is equal to 12.12, value for the whole group is equal to 19.10), but frequency 1.4 Hz imbalanced that person much more strongly. In this case, higher coefficient values were determined for this person in both variants of the coefficient. Coefficient value in the first variant, calculated from the whole FFT curve, for the participant 1 is equal to 186.50 and for the whole group is equal to 37.40. Coefficient value in the second variant, when the peak near 1.4 Hz was excluded, for the participant 1 is equal to 27.33 and for the whole group is equal to and 8.9. It means that the participant not only followed the scenery motion, but also the whole balance was disturbed. High value of the second variant of the coefficient corresponds to plenty cyclic components of high amplitude on FFT curve (Fig. 3b). These movements probably appeared as a result of participant's efforts to control imbalance.

There is another interesting fact concerning participant 1. Increase in values of time domain quantities above mean values of the whole group can be observed for this participant both in case of frequencies equal to 0.7 Hz and 1.4 Hz (Table 3). An the same time higher values of balance disturbances coefficients (both variants) occur only in the case of 1.4 Hz. This can suggest that increased value of time domain quantities in the case of 0.7 Hz does not suggest a balance problem, but it is more probable that it is related to natural body oscillation occurring in moving surroundings. Opposite conclusions can be drawn from the case when scenery oscillate with frequency equal to 1.4 Hz. Both time domain and frequency domain quantities are increased, what can be interpreted as a strong influence of this kind of scenery motion on that person. This influence can be seen both in:

- cyclic component of body movement realised with frequency 1.4 Hz
- plenty of cyclic components of body movement realised with other frequencies which can correlate to strong imbalance.

Such conclusions could not be drawn only on the basis of time domain quantities.

5. Conclusions

Balance disturbances coefficient described enables the following interpretations of the balance study:

- determination of what is the influence of the oscillating scenery on the tested subject. This analysis allows to determine to what extent the examined person bases on information coming from eyes, in comparison with the information coming from the vestibular organ and proprioception,
- determination of how the overall equilibrium was disturbed, what can be done on the basis of the second variant of the coefficient. Increased number of additional peaks with significant amplitude and high frequency may indicate that the examined person was unbalanced and attempts to prevent a fall by performing a series of additional movements. This may indicate that the system responsible for maintaining the balance is unable to cope with the sensory conflict conditions. This information can be extremely useful during medical diagnostic tests.

Current research was focused only on the use of the balance disturbances coefficient in the study of the influence of external, visual disturbances on individual participants. It is possible that there are correlations between results obtained in real and virtual environment enabling some anticipations about the ability to maintain balance only on the basis of measurements performed in the real environment, but further studies are needed.

The computer program enabling calculation of the balance disturbances coefficient will be available at www.biomechanik.pl/coefficients/bdc from June 2018.

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