The aging process in principal component analysis of posturographic signals

KRZYSZTOF PIOTR MICHALAK[1], ANNA PRZEKORACKA-KRAWCZYK[1], PAWEŁ NAWROT[1], PIOTR WOŹNIAK[2], PETER VIEREGGE[3]

[1] Laboratory of Vision Science and Optometry, Faculty of Physics, Adam Mickiewicz University of Poznań, Umultowska street 85, 61-614 Poznań, POLAND, kmichalak@amu.edu.pl, http://www.pfwio.amu.edu.pl
[2] Polish Mother's Memorial Hospital-Research Institute, OutpatientClinic, Rzgowska street 281/289, Łódź, POLAND, prw.113@gmail.com, http://www.iczmp.edu.pl
[3] Klinik fuer Neurologie, Klinikum Lippe, Rintelener Str.85, 32657 Lemgo, GERMANY, peter.vieregge@klinikum-lippe.de, www.klinikum-lippe.de

Abstract: Objective: High-pass filtering is able to remove slow oscillations in lower frequencies and releases postural reflexes with low amplitudes in the range of higher frequencies.
Methods: Principal Component Analysis (PCA) was used for determining mutual dependences between the *x* and *y* components of posturographic signals (s_2) which is defined as the ratio between the second and first components of the resulting PCA matrix. The posturographic signals in older patients with idiopathic gait disturbances were compared with those in a control group of similar age with younger patients. Additionally, the influence of the eyes whether open or closed and the head position, whether normal or bent back was analyzed. Results: MANOVA analysis proved statistically significant differences in the s_2 parameter between the groups of patients, mainly in the range of filter frequency (f = 2.2-5.5 Hz) with a peak effect at approximately 4-5 Hz. A detailed post-hoc analysis is also presented.
Conclusions: The changes in the higher frequencies range suggest that spinal reflexes are mainly disturbed, and that visual, vestibular, as well as consciousness support, appear insufficient for postural stability control. Significance: The results suggest that idiopathic gait disturbances are the next stage in the aging process of postural system.

Key-Words: postural control, principal component analysis, filtering, aging process, gait disturbance, posturography, aging

1 Introduction

Posturographic signals reflect the process of moving the center of pressure (COP) to the platform in the quiet stance and presents all the postural reflexes responsible for standing in the upright position [1]. The signal consists of 2 main components: (a) a slow drift in the center of mass in the area of low frequencies in Fourier's spectrum (f < ~0.6 Hz) [2] and (b) small oscillations with higher frequencies that reflect postural reflexes. Two components can be distinguished in postural reflexes: (a) spinal reflexes and (b) central nervous system corrections [3]. The regulatory process in spinal reflexes is the faster since it is progressing through a smaller number of synapses, and impulses have a shorter distance to travel. Central regulation takes place mainly in extrapyramidal tracts of the central nervous system with the cerebellum being the main part responsible for transferring visual, vestibular, and proprioceptive information. Central control is slightly slower, due to both the complexity of all the processes involved and the necessary to transfer information to next components of the nervous system. Two components can be distinguished here: the visual and the vestibular. When one of these components stops working, the function of the other becomes more important at the same time [4,5,6,7].
Postural control is affected by two main factors: (a) the speed at which nerve impulses are transmitted from and to the muscles and (b) the quality of the information transferred. Speed of transmission becomes lower with age. The speed depends on the quality of myelin sheaths around proprioceptive and motor fibers and on the velocity of contraction responses in muscular fibers in response to incoming action potentials.
In turn, the quality of information is influenced by the following factors: (1) the precision of the information about muscle stretching received from the receptors, (2) the number of sensory cells,

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motoneurons and intermediate neurons in the given neural area, (3) the precision with which information is transformed via intermediate neurons, and (4) the functioning of energetic processes in neural fibers. Disturbances in any of these factors can individually influence final postural stability control. However, static posturography analysis is still unable to distinguish precisely between the functioning of all these factors. Thus, one of the main aims of the present paper is to verify whether there is any possibility of performing these analyses, using advanced calculation techniques.

2 The posturographic signal

The posturographic signal reflects the number of all regulatory processes that help to keep the body in the up-right position. However, disturbances in different regulatory areas can be expected to present different features in the posturographic signal. In particular, due to the shorter duration of postural correction, disturbances in spinal reflexes are expected to be observed in higher frequencies. In turn, disturbances in the CNS are expected to occur in the lower frequencies due to longer response times. The contraction of a muscle fiber, in response to a single action potential, has approximately the shape of a reversed cosine and starts about 20-30 ms after the action potential reaches the muscle fiber. Its peak action takes place after about 100 ms and ceases after about 250 ms. The action potential in proprioceptive neurons and motoneurons is transmitted at an approximate speed of 50-60 m/s which corresponds to a total transmission time of about 10-40 ms.

Based on the above information, it can be assumed that the total time of postural correction responses will be 160-1000 ms which corresponds to a frequency of 1-6 Hz. Moreover, it can also be assumed that spinal reflexes involving a small number of synapses will be present in the range of 2-6 Hz. Finally, due to longer transfer times and a greater number of synapses, the effects of the CNS are estimated to occur in the range of about 1-3 Hz.

According to the inversed pendulum model, it is assumed that the center of mass is located at a height of 0.8-0.9 m, then the frequency of vibrations of the pendulum will be 0.6-0.7 Hz [2]. Thus, oscillations in the range of 0.6-1 Hz are related to substantial deviations in the up-right position of the human body, implying serious postural responses anomalies. In turn, oscillations below 0.6 Hz are related to a slow drift in the center of mass, rather than to postural reflexes. When compared to oscillations at higher frequencies, these oscillations are often of greater amplitude and also mask proper postural reflexes. Fourier spectra of posturographic signals are characterized by the amplitude decreasing while frequencies are increasing. Thus, analysis of signals at different frequencies requires, first of all, the removing of lower frequencies from the signal in order to reveal higher frequencies with lower amplitude.

2.1 The division of posturographic signals into their components

The separation of posturographics signal into the components that relate to individual regulatory processes in the nervous system is a complex process. Amoud et al. [8] divided the posturgraphic signals in young and older subjects, using Empirical Mode Decomposition (EMD), into 4 components whose mean frequencies were about 0.5 Hz, 1-1.5 Hz, 3-4 Hz and 6-8 Hz. These components showed age-related differences in the parameter of 'Area of Hilbert transform' and 'Average Rotation Frequency'. A similar decomposition was also shown by Ramdani et al. [9]. Amoud et al. [8] also showed differences between age groups, using basic-EMD with separate analyses for x and y, and complex-EMD where the common relation between x and y components is not removed. Maatar et al. [10] propose Discrete Wavelet Decomposition and modified PCA to decompose the stabilogram into three components which he called trend, rambling, and trembling.

The application of digital filters to posturographic signals is rather sparse. Horlings et al. [6] showed that patients with bilateral lower-leg proprioceptive loss are characterized by other shoulder to pelvis characteristics in >3 Hz high-pass filtered signals from body-worn gyroscopes mounted at the pelvis and shoulders.

A series of digital high-pass filters in the range of f = 0.05-6 Hz was used in the present study. However, one should remember that postural corrections may be achieved through rapid changes in COP-direction. Such changes are characterized by a wide spectrum in Fourier analysis with a decreasing amplitude for increasing frequencies (See Fig. 2 spectrum of triangular signal). As a result of this, high-pass filters will not be able to remove lower frequency components precisely. In practice, the presented effect is reduced because corrective reflexes are not precisely triangular-shaped. However, the discrimination value for different parameters of the filtered signals can be lowered for this reason. This problem needs to be address both theoretically and empirically.

A method which only partially relies on the spectrum of given components is Principal

Component Analysis (PCA). The problem that occurs with this method involves matrix that will be next orthogonally rotated using PCA. With a standard posturographic signal it is possible to incorporate x and y components into this matrix (spatial decomposition) or to incorporate the same signal but shifted in time (temporal decomposition). It is important to stress that, up to now, little is known about using the PCA method in the analysis of posturographic signals. This method has been applied to compare different parameters calculated from non-filtered signals, rather than to perform spatio-temporal decomposition of the signal itself [11,12,13].

In addition, the removal of slow frequencies that reflect a slow drift of the center of mass was not included in earlier studies. Therefore, the process of filtering and other methods for decomposing posturographic signals, may prove a helpful tool in developing new and innovative methods of diagnosis using posturography.

3 Materials and methods

3.1 Subjects

Posturographic signals were recorded in the Neurology Clinics of Luebeck Medical University. The investigation adhered to the principles of the Declaration of Helsinki and was approved by Ethics Committee at the Universität zu Lübeck, Germany. Additionally, informed consent was obtained from subjects after the explanation of the aim of the procedure.

A total of 384 subjects were included in the study. In order to examine the influence of the aging process on the parameters of posturographic signals, the patients were divided into 4 groups: 3 age-fitted groups of normal patients (B_1-B_3) and a group of older patients with idiopathic gait disturbances (A). There were 54 patients in group A, aged average 81.9 ± 6.5. Next, 98 normal patients aged average 76.5 ± 4.1 were in group B_1, 193 normal patients aged average 61.6 ± 5.2 were in group B_2, and finally 39 normal patients aged average 30.1 ± 5.6 joined group B_3. Group A included patients who either (a) reported nonspecific gait disturbances resulting in stumbling or even falling during the previous six months, or (b) were previously neurologically diagnosed with having an unexplained or unclassified gait disorder. Patients were not included if the gait disorder could be explained by one or more of the following conditions: hemi-, para-, tetraspasticy or -paresis, any kind of myopathic, myelopathic, cerebellar, vestibular, brainstem or neuropathic lesions, any degenerative disease of the central or peripheral motor system, intake of CNS-relevant drugs and any medical, orthopedic or dermatologic impairment interfering with gait.

Normal patients who did not show any deviations at the preliminary neurological examination were included in groups $B_{1\text{-}3}$. These healthy participants had to show an inconspicuous gait pattern and had to be able to perform six tandem steps without deviation during at least one of two subsequent trials.

3.2 Apparatus & procedure

The participants stood upright, with their feet 80 mm apart on a force-measuring platform. COP displacement was registered in the antero-posterior (y coordinate) and medio-lateral (x coordinate) directions under static conditions. Recordings of the signal were performed 4 times for each participant under different conditions in respect to eyes state and head position: (1) eyes open (E_O) and normal position of the head (head normal H_N); (2) eyes closed (E_C) and H_N; (3) E_O and standing with head maximally pulled back (head bent back H_{BB}; vestibular stimuli partially excluded from balance control); (4) E_C and H_{BB}. In the E_O condition, the participants fixed their gaze on a small dot drawn on the wall at gaze level and a distance of 2 m. Pressure forces were digitized at the sampling rate of 50 Hz. All data were recorded for 30 s, but only the last 20.48 s were taken into further analysis. The initial interval of 9.52 s was treated as a posture stabilization period [14]. Each sweep, therefore, had 1024 2-dimensional data points.

3.3 Signal analysis

3.3.1 Filtering and Principal Component Analysis

Components x and y of the signal were first filtered, using high-pass filters which removed the low-frequency components of the signals. Signals were filtered using FIR digital filter (Matlab®) with a filter order R = 300. Analysis was performed for 30 different high-pass filters ranging from f = 0.05 Hz to 6 Hz. After filtering, the x and y signal were normalized: $x_n = \left(x - \bar{x}\right)/\sigma_x$ and $y_n = \left(y - \bar{y}\right)/\sigma_y$.

Next, the PCA method (Principal Component Analysis) was applied. As a result, orthogonal rotation of the data matrix was created in order to maximize variations in the successive columns of resultant matrix. The matrix analyzed using PCA was constructed from 4 columns: I: x_n(1-1023), II: x_n(2-1024), III: y_n(1-1023) and IV: y_n(2-1024). Columns I-II and III-IV reflect the same signals but

shifted in time by one sample (i.e. t = 0.02 s), hence, the columns are strongly correlated. Applying the PCA method to this pattern of columns leads to a division into a signal (first) component and the noise (second) component [15]. Constructing the matrix analyzed by the PCA method from 2 shifted *x* signals and 2 shifted *y* signals makes it possible to determine the mutual relation between the *x* and *y* components and to remove about half of noise from these components [15]. As a result, after applying the PCA method to the 4-column matrix, the resultant matrix mainly includes the *x* and *y* components in columns I and II, while in columns III and IV the matrix mainly contains noise. Singular Values (*S*) of the resultant matrix are approximately proportional to the standard deviations of successive columns. A detailed analysis was made of the ratio between columns II of *S* (S_{II}) and column I (S_I) ($s_2 = S_{II}/S_I$), which refers to the mutual relation between the x_n and y_n components. When the parameter s_2 is about 1, there is no relation between the x_n and y_n components. The lower the s_2 value, the greater the relation between signals x_n and y_n.
The aim of the experiment in the present paper was to determine any mutual relation between the x_n and y_n components of posturographic signals in different groups of normal patients and in the group of patients with idiopathic gait disturbances.

3.3.2 Surrogate signals

In order to determine whether the results obtained are based on reliable observations and reflect the true characteristics of the signal, the values of the s_2 parameter of the original signals was compared to those of their surrogates. The surrogate is a stochastic signal that possesses the same Fourier spectrum as the original signal, but the phases of successive frequencies are randomly shuffled in order to destroy any information in the signal. The 'Surrogate 2' algorithm was used in this work [16,17].
Figure 1 presents the mean spectra of the signals analyzed. Figure 1a presents the mean spectra for group A and $B_{1\text{-}3}$ averaged from all the registration methods, $E_{O/C}H_{N/BB}$ and the *x* and *y* components. Next, Figure 1b the presents the spectra for registration methods for $E_{O/C}H_{N/BB}$ averaged from all groups of patients and their *x/y* components. Finally, Figure 1c presents the *x* and *y* components averaged from all groups of patients and the $E_{O/C}H_{N/BB}$ registration methods.
These figures are made in logarithmic scale. Three areas can be distinguished here: I: $f < 1.2$ Hz - with smoother slope ($a \approx -0.7$), II: $f = 1.2\text{-}20$ Hz - with steeper slope ($a \approx -1.4$), and III: $f > 20$ Hz - horizontal noise area.

4. Results

4.1 The signal spectrum

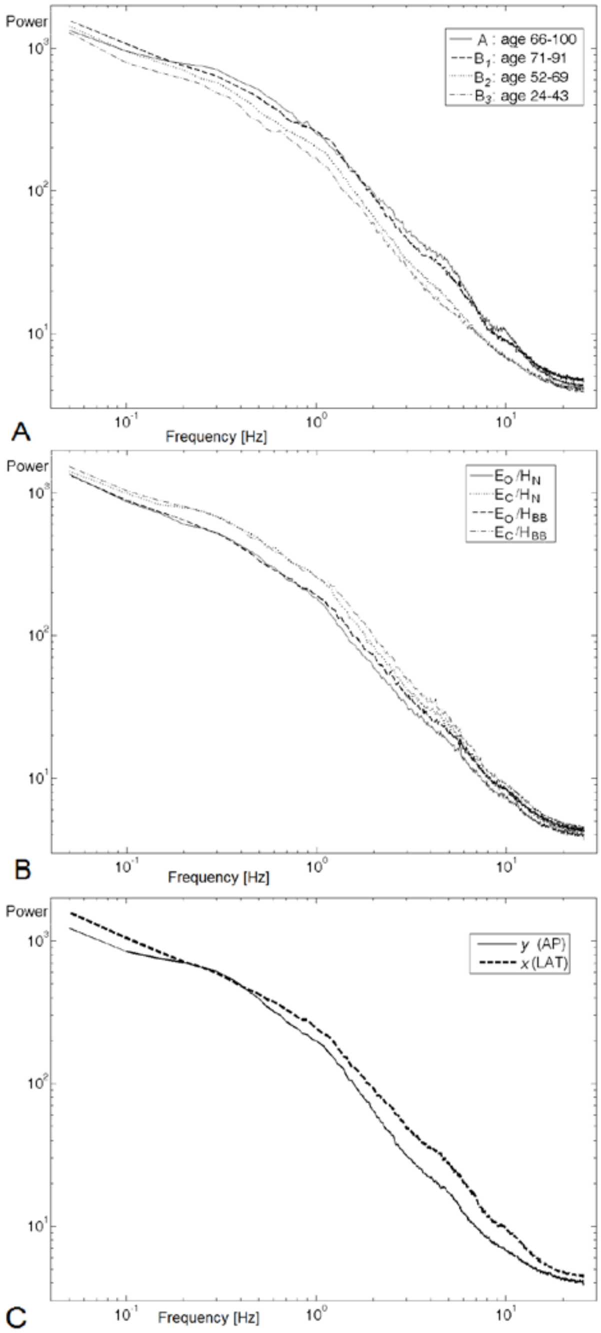

Fig. 1. Spectra of posturographic signals. A: Mean values for given groups of patients (estimated for different registration methods and for both *x/y* components), B: Mean values for given methods of signal registration (estimated for all groups of patients and for both components), C: Mean values for *x* and *y* components of the signal (all groups of patients and all registration methods).

Figure 1a shows an increase in mean amplitude in the group of older patients (A and B_1) in all frequencies. Also, little increase in amplitude in the frequency of 2-5 Hz and about 10 Hz is observed here, which suggests that these ranges of frequency may carry useful diagnostic information that would refer to the process of aging or neurological disorders. Figure 1b shows the differences in spectrum between different methods for signal acquisition: $E_{O/C}H_{N/BB}$. As the figure shows, when the patient closes the eyes, amplitude is increased in the range of lower frequencies below 1 Hz which relates to greater slow drift in the center of mass. However, in the 2-10 Hz range of frequency it is observed that a low increase in amplitude is caused by closed eyes or head bent back. A higher increase in amplitude is, in turn, observed when the patient has the eyes closed and the head bent back. So, it can be concluded that both factors *Eyes* and *Head* lead to the independent increase in amplitude of oscillation.

Figure 1c shows that, in the range of frequencies f = 2-15 Hz, the amplitude is higher for component x than for y.

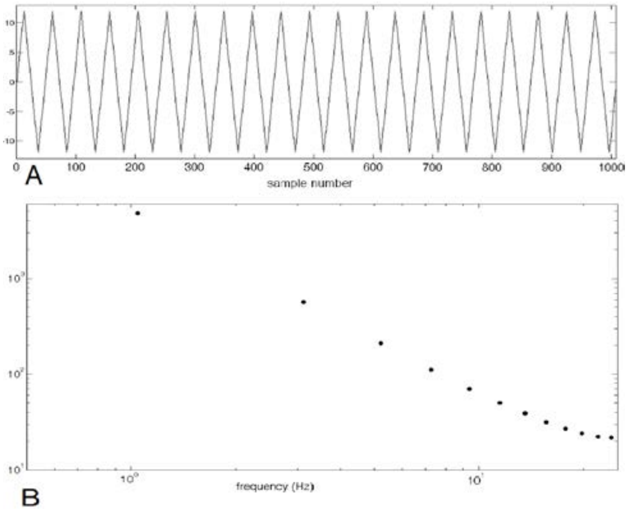

Fig. 2. An example of a triangular signal (A) and its Fourier spectrum (B). The directional coefficient of the straight line fitted to spectrum points is a = -2. The example highlights one of the possibilities for the frequencies f > 6Hz to occur in the spectrum of posturographic signals as the components of oscillation with lower frequency and a non-sinusoidal shape.

Theoretically, the regulatory mechanisms of the neural system basically rule out the possibility of components having frequencies greater than f = 6 Hz. The occurrence of such frequencies in the spectrum can be explained by means of the exemplary triangular signal. Figure 2a presents an example of this signal at a frequency of f = 1.042 Hz obtained through a sampling frequency of 50 Hz. The Fourier spectrum of this signal is presented in Figure 2b. As the latter figure shows, the spectrum is linear in the logarithmic scale and the directional coefficient of the straight line fitted to spectrum points is a = -2. Hence, it can be hypothesized that frequencies in the spectrum higher than 6Hz are the components of the lower frequency oscillations that are close to triangular.

The occurrence of frequencies (f > 6Hz) in the posturographic spectra may suggest the existence of sharp and rapid corrections for the deflections from the equilibrium point in the postural system that are especially observed in the elderly.

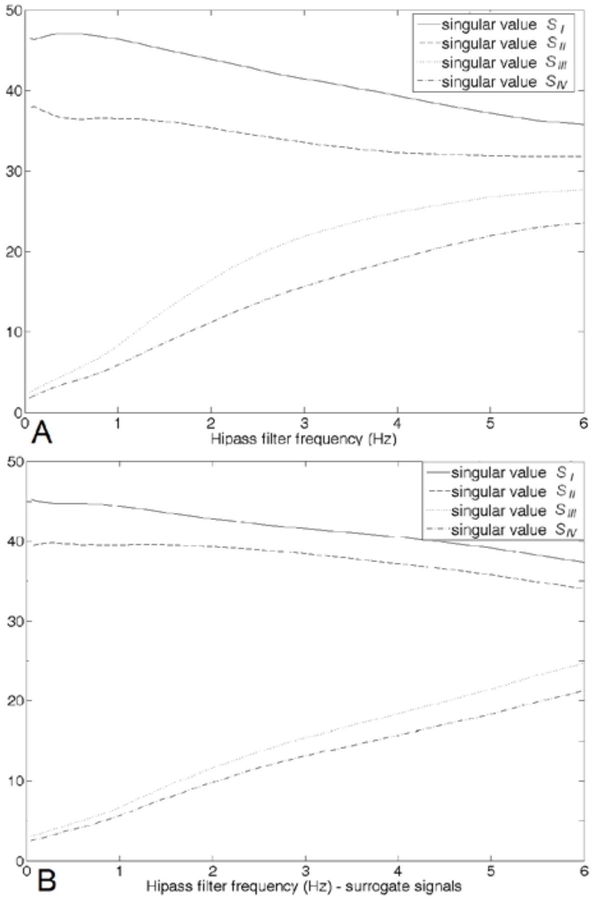

Fig. 3. Singular values of S_I-S_{IV} obtained from Principal Component Analysis for different frequencies of high-pass filters f = 0.05-6 Hz. A: original signals, B: shuffled signals. S_I and S_{II} represent mainly the x and y components of the signal, while S_{III} and S_{IV} represent mainly noise. Note that the bigger difference between S_I and S_{II} for the original signals than for the surrogates points to dependence between the x and y components in the original signals.

4.2 Singular values

Figure 3 shows the mean values of four singular values S_I-S_{IV} for the analyzed signals after high-pass filtering in the range of frequency f = 0.05-6 Hz. Figure 3a presents the results from the analysis of original signals, while Figure 3b presents the results from the analysis of surrogates. As this figure shows, when compared to surrogates, original signals have lower S_{II} in favor of S_{III} . In the case of

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surrogates, the common relation between x_n and y_n is lost, which makes S_{II} and S_I components similar and $s_2 = S_{II}/S_I$ is approximately equal to 1. The components S_{III} and S_{IV} contain mainly the noise. The general increase in the prevalence of S_{III} and S_{IV} with increase in the filter frequency, is caused by the growing role of the noise in the analyzed signals after filtering. For $f > 5$ Hz, postural oscillation is observed to be only slightly higher than the noise level and filtering analysis was therefore limited to 6 Hz. Analysis in the range of f = 6-20 Hz requires higher frequency of signal sampling and lower noise level during signal registering.

4.3 MANOVA analysis

The present analysis was based on the value of the s_2 parameter which refers to the relation between components S_I and S_{II} after applying spatio-temporal PCA. MANOVA analysis was performed on the set of available data. The analysis focused on the following factors: the 4 groups of patients ($A/B_{1\text{-}3}$), head position (2 groups: H_N, H_{BB}), eyes state (2 groups: E_O, E_C), and signal shuffling (2 groups: original/shuffled). The analysis was performed separately for every high-pass filter frequency (30 values: f = 0.05–6 Hz).

4.3.1 Effect of the shuffling procedure

The first part of the research examined the effect of shuffling procedure on the obtained results. Figure 4 presents the results for original signals and surrogates. The lines in Figure 4 refer to the mean values for all groups, and separately for every *Eyes/Head* condition. Figure 4 shows that the values of the s_2 parameter are lower for the original signals in all filter frequencies, and all *eyes/head* conditions. The post-hoc analysis performed using the Newman-Keulus and HDS Tukey tests separately for every frequency, every *eyes/head* conditions, and for all the patients' group, proved that differences in the s_2 parameter between the original signals and surrogates are significant ($p < .001$) in all the cases analyzed.

4.3.2 Analyzed groups

Further analysis focused on the original signals only. The effect of the different patient groups in MANOVA analysis occurred statistically significant ($p < .001$) in an analysis performed for all frequencies and registration methods. Since the results appeared different for different filters used in the study, the further analysis was performed separately for every frequency of the filter.

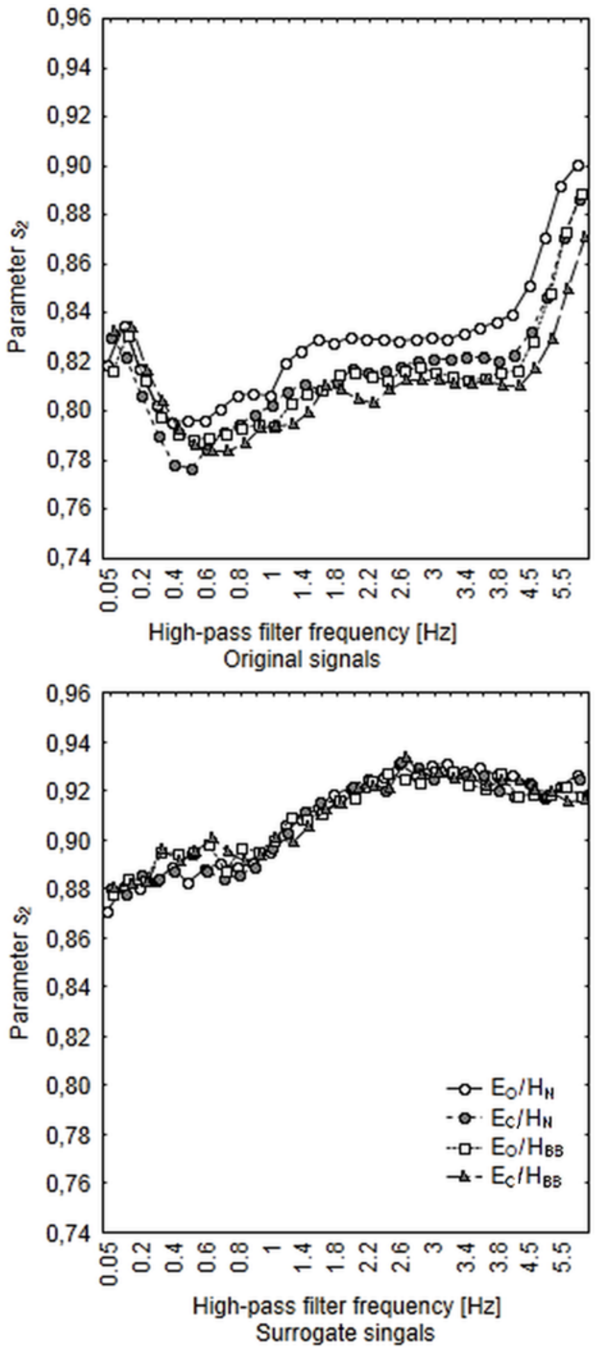

Fig. 4. Mean $s_2 = S_{II}/S_I$ for original signals (left) and surrogate signals (right) calculated for different high-pass filters and *Eyes/Head* conditions. Mean for 4 the patients' groups. E_O – eyes open, E_C – eyes closed, H_N – head normal, H_{BB} – head bent back. The differences between the original and surrogate signals are significant for all filter frequencies, for every *Eyes/Head* conditions and all the patients' groups analyzed ($p < .001$).

Figure 5 presents the s_2 values for the four patient groups with 95% confidence intervals. These values refer to the mean values of the s_2 parameter. The upper part of Figure 5 presents the mean values for all eyes and head conditions together, while the lower part presents the mean values for eyes and head conditions separately. The upper figure shows considerable variations in the value of parameter s_2 for all the patient groups in the range of filters frequency f = 2.2-6 Hz. The figure also includes statistically significant values for post-hoc analysis, using the Newman-Keuls test, between groups A vs. B_1, B_1 vs. B_2 and B_2 vs. B_3. Comparison between groups A and B_1 revealed an increase in statistical significance for filter frequencies $f \geq 2.2$ Hz. Next, comparison between groups B_1 and B_2 revealed a statistical significance of $p < .05$ only for the frequency f = 5-6 Hz. Finally, comparison between groups B_2 and B_3 proved statistically significant in the 3 Hz to 5.5 Hz range of filter frequency with the maximum observed being for f = 4.5-5 Hz. The results obtained show that filtering posturographic signals or other decompositions, may prove useful in establishing reliable diagnostic criteria. The considerable differences in the s_2 parameter for each patient group allow us hypothesize that major disorders of the postural system connected with the aging process may relate to segmentary reflexes of the spinal cord and to their direct modulations via visual or vestibular passages. It can be concluded that the relation between the x and y component increases with age. In the 2.2-5 Hz range a gradual increase in the discrimination value between groups can be observed, with its maximum occurring in the frequency of about 4.5 Hz. This frequency appears to be high enough to remove the effects of slow drift and central regulation, and at the same time, it is low enough to preserve a major part of the spinal component in the signal. With frequency above 4.5 Hz, one can observe a gradual increase in the s_2 parameters up to the values recorded in surrogates. The results obtained suggest that idiopathic gait disturbances are the next step in the aging process of the postural system.

4.3.3 Eyes state/Head position

The bottom part of Figure 5 presents the results from the upper part of Figure 5 divided into 4 types of *Eyes/Head* position. This figure shows for $f > 2$ Hz a weak tendency for s_2 to decrease when the eyes are closed and the head is bent back. However, most importantly the s_2 parameter is observed to decrease substantially with age, which next leads to the prevalence of idiopathic gait disturbances. In order to examine the effect of eyes and head position on the s_2 parameter, a set of post-hoc analyses, using the Newman-Keuls test, was performed. Out of 3 parameters: 'patient group', 'eyes state', 'head position', one factor was analyzed against the given values of the others. Table 1 shows the results from these analyses.

The upper part of the table shows filter frequencies for which differences in s_2 are significant for different conditions of one factor (*Eyes/Head)* and for a fixed value of the second factor.

Group	Fixed Param.	Analyzed Parameter	Filter frequencies with significant difference
A	E_O	H_N vs H_{BB}	--
	E_C	H_N vs H_{BB}	--
	H_N	E_O vs E_C	--
	H_{BB}	E_O vs E_C	0.05Hz
B_1	E_O	H_N vs E_{BB}	0.05 Hz, 0.6 Hz, 5.5 Hz
	E_C	H_N vs H_{BB}	--
	H_N	E_O vs E_C	5.5 Hz
	H_{BB}	E_O vs E_C	--
B_2	E_O	H_N vs H_{BB}	0.8-1.6 Hz, 3.0-5.0 Hz (3.4-4.5 Hz*)
	E_C	H_N vs H_{BB}	--
	H_N	E_O vs E_C	0.4-0.5 Hz*, 0.6 Hz, 1.6 Hz, 3.8 Hz, 4.0-5.0 Hz *
	H_{BB}	E_O vs E_C	2 Hz, 5.5 Hz
B_3	E_O	H_N vs H_{BB}	0.6-0.9 Hz
	E_C	H_N vs H_{BB}	0.3-0.5 Hz, 5 Hz
	H_N	E_O vs E_C	0.7-1.0 Hz
	H_{BB}	E_O vs E_C	--

Eyes/Head Condition	**Group**	**Filter frequencies with significant difference**
E_OH_N	A vs B_1	0.05-0.2 Hz, 3-6Hz (5.0-5.5 Hz*)
	B_1 vs B_2	0.05 Hz, 0.5-1.1 Hz, 3.8-5.0 Hz
	B_2 vs B_3	4.0-5.0 Hz
E_CH_N	A vs B_1	--
	B_1 vs B_2	5.5 Hz
	B_2 vs B_3	3-5 Hz (4.0-5.0 Hz*)
E_OH_{BB}	A vs B_1	3.8-6Hz
	B_1 vs B_2	5.5 Hz
	B_2 vs B_3	--
E_CH_{BB}	A vs B_1	2.2-4.0 Hz
	B_1 vs B_2	5.5 Hz
	B_2 vs B_3	1.6 Hz, 2.6-3.2 Hz

Table 1. Post-hoc analysis. (*) – significance $p<0.01$

This analysis proves the effect of eyes closed or head bent back on the value of the s_2 parameter. Significant differences were most prevalent in the $f < 1$ Hz filter frequency. The results appear to correlate with observations that show an increase in amplitude of low-frequency oscillations when eyes are closed and/or the head is bent back, which causes the increase in path length and in surface area covered by the track of COP [18,19].

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4.3.4. Correlation with age

The lower part of Table 1 shows the significance of s_2 differences between neighboring patient groups for the different registration methods. It therefore shows which factors influence, to the highest degree, the aging process in their period of life. The highest correlation of the s_2 parameter with age is observed in the $f > 2$ Hz frequency range. The dominant role for this frequency range is postulated to depend on spinal reflexes, and their possible corrections through direct connections coming from visual and vestibular subcortical nuclei.

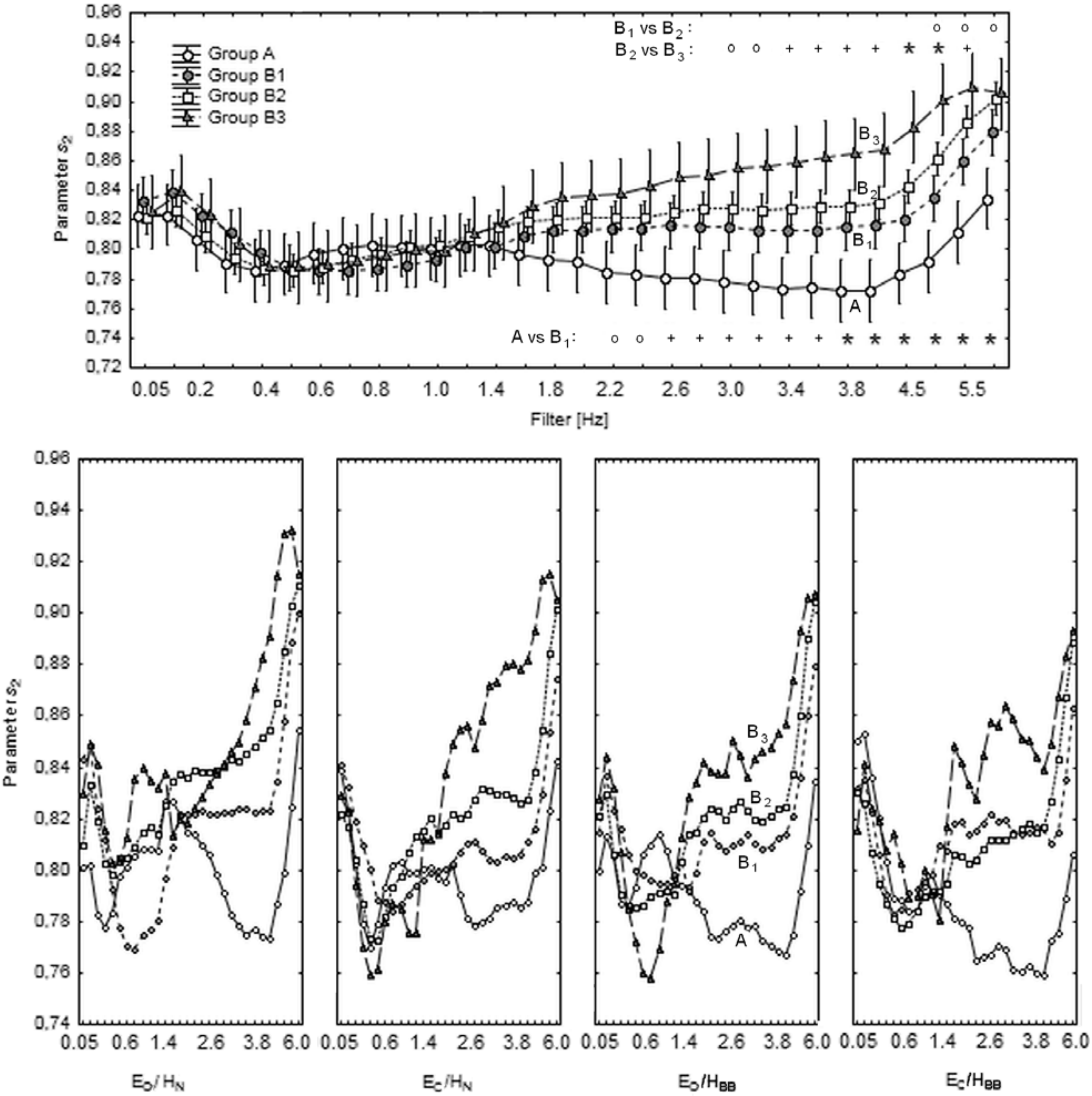

Fig. 5. Upper part - mean s_2 values for the 4 groups of patients calculated over 4 Eyes/Head conditions. Lower part - each Eyes/Head condition recorded separately. E_O – eyes open, E_C – eyes closed, H_N – head normal, H_{BB} – head bent back. Marked range denotes 95% confidence interval. Significant differences in $p = .05$ are marked with (o), in $p = .01$ with (+), and in $p < .001$ with (*).

In the range of $f > 2$ Hz frequency significant differences are only observed in group B_2, where the value of s_2 is substantially decreased when the eyes are closed or the head bent back (E_O, H_N vs. H_{BB}: $p < .01$ for $f = 3.4\text{-}4.5$ Hz; H_N, E_O vs. E_C: $p < .01$ for $f = 4\text{-}5$ Hz). These results suggest that for those over 60 (group B_2) both visual and vestibular support is necessary to keep a good quality of postural control. Lack of one of these factors leads to a deterioration of postural control.

The significant differences observed for $f = 5.0$ Hz filter frequency (B_3, E_C, H_N vs H_{BB}: $p < .05$) and for *f* = 5.5 Hz (B_1, E_O, H_N vs. H_{BB}: $p < .05$; B_2, H_{BB}, E_O vs. E_C: $p < .05$) may suggest the existence of the rapid, (triangular-shaped) corrections at lower frequencies that provide the increase in amplitude of the $f > 5$Hz frequencies in the spectrum.

A comparison between subjects in group B_2 (mean age 61 yrs) and group B_3 (mean age 30 yrs) shows the highest statistical significance for the E_CH_N registration pattern ($p < .01$ for f = 4-5 Hz). This result suggests that the role of labyrinth in the postural stability becomes greater when the patient has the eyes closed. The decrease in s_2, if only the labyrinth supports postural control suggests that, in the age range of 30 to 60 years, the aging process of the vestibular system deteriorates postural stability to a higher degree than the aging process of the visual system. A lesser role that of the deterioration of visual support, may be a explained by a lowering of the s_2 parameter in the E_OH_N registration pattern ($p < .05$ for f = 4-5 Hz). In turn, s_2 is becoming lower for E_CH_{BB} ($p < .05$ for f = 2.6-3.2 Hz). This may suggest that modulations other than visual or vestibular ones may also be weakened (possible in the cerebellum/spinal cord). The lower range of frequency may be the result of higher, thus slower, oscillations when both eyes are closed and the head is bent back or alternatively may suggest a weakening of higher regulation levels.

Comparison between group B_1 (mean age 76 years) vs. B_2 (mean age 61 years) suggests that significant differences occur with the classic registration pattern E_OH_N ($p < .05$ for f = 3.8-5 Hz).

It can be concluded that at this stage of the aging process, visual modulation is becoming weakened, followed by a weakening of vestibular modulation, but to a lesser extent. It can be seen that in the B_2 group the visual and vestibular systems working together make it possible to maintain the 'juvenile' regulation processes which are not observed in group B_1 where s_2 is lowered approximately to a similar level in each registration method.

Comparison between groups A and B_1 shows a further lowering of s_2 for all registration methods (E_OH_N: $p < .05$ for f = 3-6 Hz, $p < .01$ for 4-5 Hz; E_OH_{BB}: $p < .05$ for f = 3.8-6 Hz; E_CH_{BB}: $p < .05$ for f = 2.2-4 Hz). The differences are not statistically significant for E_CH_N only. The above results suggest a further general deterioration in the functioning of segmental correction reflexes, a further weakening of the influence of the visual system on postural stability, as well as a slightly lesser weakening of the vestibular system on postural stability.

5. Discussion

The results of the analysis of the s_2 parameter of high-pass filtered posturographic signals suggest that filtering the posturographic signal gives a potentially high possibility of obtaining significant diagnostic parameters. It is expected that the signal parameters calculated for filtered signals will have higher discriminatory values than those for non-filtered signals.

Though the process of filtering is unable to provide a complete division of the signal into components coming from different parts of the postural control system, it is still possible to find statistically significant differences in given age groups for different filter frequencies. Filtering is able to remove major slow oscillations with high amplitude and, at the same time, is able to release postural reflexes that are active in the 1-6 Hz range. In the present experiment the differences were observed mainly for the $f > 2$ Hz frequency.

Filter order is an important parameter in the process of filtering. The maximum filter order possible to use is 1/3 of the signal length [20]. In the case of our analyzed signals it was R_{max} = 1024/3 = 341. The higher the filter order, the sharper the border of low frequency cut off is in the spectrum. A submaximal filter order (R = 300) was used in the present study to make the filtering effective. It must be pointed out, however, that if other acquisition times and/or sampling frequency were used, then a filter order giving the same filtering properties as in the current paper would be other than R = 300.

The results obtained help to determine the mean intensity of the aging process in studied elements of the postural system. Between 30 (B_3) and 60 yrs (B_2), the weakening of the vestibular component is more visible than that of the visual one. Hytonen et al. (1993) showed, that older individuals rely more on visual cues to keep stable posture. Next, between 60 (B_2) and 76 yrs (B_1), a further weakening of the two components is observed, with weakening of the visual component progressing the faster. In group B_1, the effects of the visual system and/or the vestibular system on the s_2 parameter are small, since neither system is able, at this point, to enhance the functioning of postural control.

The integrity of the CNS determines the attentional demands needed to maintain proper posture (Dault et al., 2001). As Jacobs and Horak (2007) claimed, conscious attention starts to play a major role in postural stability in the elderly, which is manifested by deteriorating postural parameters during mental activities. The present paper considers idiopathic gait disturbances as the next stage in the weakening of postural functions, as a result of which postural stability becomes hard to sustain even when the patient is fully concentrated.

However, it should be stressed that the results obtained in the present paper must be treated as only a pilot ones. The s_2 parameter is only one of the possible parameters to use in a study that only partially describes the postural system. It is possible that other parameters calculated for filtered signals will better discriminate between different patient groups.

Also, one should remember that it is possible to use more advanced methods for dividing posturographic signals into their components, and for removing noise using spatio-temporal PCA. Registration with higher sampling frequencies and lower noise levels will ensure greater precision and accuracy of low-amplitude and high-frequency components in the signal and will allow for expanding the range of filters above the 6 Hz used in the present paper.

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