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Postural Symmetry Evaluation Using Wavelet Correlation Coefficients Calculated for the Follow-Up Posturographic Trajectories

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Abstract—**The paper presents an original method enabling postural symmetry evaluation using weighted averages of the wavelet correlation coefficients obtained individually for the corresponding x and y components of the cantered follow-up posturographic trajectories registered during the clockwise and counterclockwise visual stimulations. In the process the x and y components of both trajectories undergo 7-stage db2 discrete wavelet decomposition. The correlations of the detail coefficients are evaluated at all levels of the decomposition structure whereas the correlations of the approximation coefficients are calculated only at its last level. Applied weighting factors constitute the sums of energies of the reconstructed details or approximations corresponding to a particular level of decomposition. The ultimate measure of postural symmetry in the herein presented method is the quantity based on the vector distance of the point whose coordinates constitute the values of the obtained weighted correlation coefficients (individually for the x and y components), from the point representing the state of ideal symmetry. This quantity assumes the values within the range of [0,1], where 1 is identified with the maximum postural symmetry dynamics whereas the value of 0 represents the state of maximum anti-symmetry dynamics (analysed trajectories are out of phase by π [rad]). The applicability of the herein presented method was verified in the process of postural symmetry evaluation carried out in the group of 30 patients rehabilitated after total hip arthroplasty.**

Index Terms—**Correlation; discrete wavelet transform; follow-up posturography; postural symmetry evaluation.**

I. INTRODUCTION

Posturography is a non-invasive diagnostic method enabling objective and quantitative evaluation of the human body's postural stability, providing valuable information on the performance of the human balance system [1]. In essence, it boils down to registration and analysis of the CoP (Center of Pressure) trajectories which represent the movement of the point of application of the net downward force exerted by a person's body on his or her support plane [1], [2]. Measurement of the CoP trajectories is conducted on the posturographic platform, which is a specialized sensory device equipped with a set of gauge transducers transforming the downward forces exerted by an examined person standing on the platform into electrical signals [2], [3]. After ADC conversion of these signals, the data are sent to a computer, where the posturographic analysis is carried out. Measurement of the CoP trajectories can be performed on a single-plate or double-plate measurement platforms [4], [5]. In the former case one obtains the so-called central CoP trajectory, which is the average of the CoP trajectories of the right and left lower limbs. In the latter case the CoP trajectories are obtained independently for each of the lower limbs. The double-plate posturographic platform provides much more information on the performance of the human balance system, however, it's also a much more expensive device.

There are three major types of posturography: static, dynamic and the so-called follow-up posturography [5], [6]. In case of the static posturography diagnostics an examined person is standing on the measurement platform in an upright and relaxed position. During the measurement the platform is registering small swaying and involuntary movements of the body. There are no deterministic external stimuli which could interfere with the body's postural stability mechanisms [4]. The static posturography examination can be performed with patients having their eyes open or closed.

The dynamic posturography is a more advanced diagnostic method, utilizing external stimuli which mechanically disturb the examined person's postural equilibrium. The response to such stimulations is then analysed in terms of the body's ability to restore postural stability. The dynamic posturography utilizes specialized servo motors enabling rotation of the support plate and/or visual surround with a given velocity. It should be noted the equipment required to perform this is kind of diagnostics is very expensive [6], hence the use of the dynamic posturography is not so commonplace.

Particularly interesting type of posturography is the follow-up posturography which combines the most desired features of the static and dynamic measurement approaches. During the follow-up posturography examination a person is

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standing on a measurement platform, balancing his or her body in such a way that the CoP trajectory visualized on the monitor screen situated in front of the subject coincides with the trajectory of the deterministic visual stimulation also presented on the screen [4]. This kind of examination can be a valuable source of information on the dynamic performance of the human balance system, unachievable in case of a typical static posturography. It's worth noting that the follow-up posturography examination can be performed on a measurement platform used for a typical static posturography diagnostics. This makes the follow-up posturography a cost-effective alternative to a much more expensive dynamic approach.

Most of the posturographic symmetry measures today are based on quantification of the CoP trajectories obtained for the left and right lower limbs, registered during static posturography examinations (*e.g.* length of the trajectory, surface area under the unrolled trajectory, average deviation from the center of the trajectory) [4], [5]. While performing the static posturography examination one can also calculate average weight distribution of the examined person's body, which is an equivalent of the so-called test of two scales [7]. In medical practice today posturographic coefficients quantifying postural symmetry are calculated either as the differences of the absolute quantities obtained for the left and right lower limb or relative quantities being the ratios of the absolute quantity obtained for one of the limbs and the sum of quantities obtained for each limb individually (1). The second approach is more effective as the relative measures of symmetry minimize the dispersion of the absolute quantities obtained for individual patients, emphasizing the differences in performance of the left and right lower limb. The formula (1) represents a generalized relative symmetry measure [4], [5]

$$S_x = \psi_E / (\psi_R + \psi_L), \tag{1}$$

where S_x – relative symmetry measure, ψ_L, ψ_R, ψ_E – absolute measures corresponding to the left limb (ψ_L), right limb (ψ_R) and the limb for which the relative quantity is calculated (ψ_E), respectively.

Instead of quantity S_x, one can use the ΔS_x measure expressed by (2), which quantifies the absolute deviation of the S_x value from the value identified with the state of ideal postural symmetry (0.5) [5]

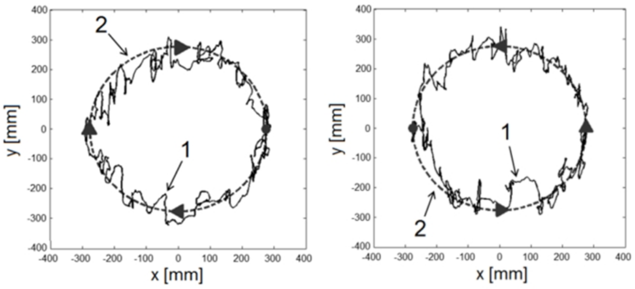
$$\Delta S_x = |0.5 - S_x|. \tag{2}$$

None of the aforementioned postural symmetry measures, however, is designed to evaluate postural symmetry in dynamic conditions with the presence of an external stimuli, imitating the real-life existence.

In the next section of this paper the reader will be acquainted with an original method of postural symmetry evaluation based on the follow-up posturography examination. The method enables wavelet and correlation-based assessment of similarity between the slow swaying movements of the left and right lower limb registered in response to visual stimulations similar from the perspective of each limb.

II. METHOD OF POSTURAL SYMMETRY EVALUATION USING WAVELET CORRELATION COEFFICIENTS CALCULATED FOR THE FOLLOW-UP POSTUROGRAPHIC TRAJECTORIES

In the herein presented method the follow-up posturographic trajectories registered for the clockwise and counter-clockwise visual stimuli are analysed. Applied stimulations are circular and have a constant angular velocity [8]. Figure 1 illustrates the visual stimulations with the corresponding sample follow-up trajectories.



a) b)

Fig. 1. Sample follow-up posturographic trajectories (1) registered for the clockwise: (a) and counter-clockwise (b) visual stimulations (2).

The x and y components of the clockwise and counter-clockwise follow-up posturographic trajectories undergo processing in the cascade of low pass and high pass filtering stages, implementing 7-stage db2 discrete wavelet transform, in other words, 7-stage discrete wavelet decomposition using db2 mother wavelet (Fig. 2 and Fig. 3) [9]–[11].

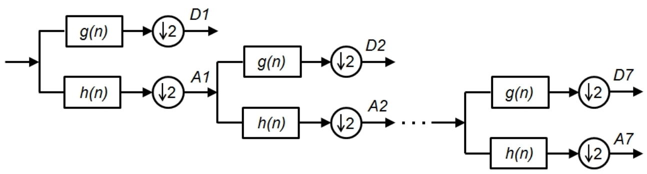
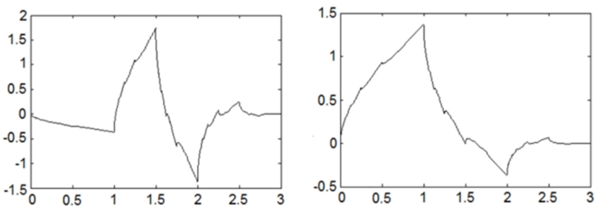


Fig. 2. The 7-stage discrete wavelet decomposition structure, where *g(n), h(n)* represent impulse responses of the high pass filter and low pass filter, respectively. Symbol ↓2 depicts decimation block whereas *D1-D7* and *A1-A7* are the detail and approximation coefficients, respectively.



a) b)

Fig. 3. Approximations of the db2 wavelet function (a); and the associated scaling function (b).

Detail coefficients *D1-D7* and approximation coefficients *A7* obtained for the *x* coordinate of the clockwise trajectory are correlated with the detail coefficients *D1-D7* and approximation coefficients *A7* obtained for the *x* coordinate of the counter-clockwise trajectory. Exactly the same happens for the *y* coordinate.

Wavelet correlation coefficients are calculated using the following formula:

$$C_r(a,b) = \left(\sum_{n=0}^{N-1} a[n]b[n]\right) \Bigg/ \sqrt{\sum_{n=0}^{N-1}\left(a[n]^2 + b[n]^2\right)}, \quad (3)$$

where C_r – wavelet correlation coefficient, a, b – correlated detail or approximation coefficients, N - total number of coefficients on a given level of decomposition, n - current coefficient number.

The measures quantifying postural symmetry in this method are calculated independently for the x and y coordinates of the follow-up trajectories, constituting the weighted averages of the correlations obtained for the details and approximation coefficients on the corresponding levels of the wavelet decomposition (4), (5):

$$\gamma_x = -\frac{1}{\sum_{i=1}^{k} E_{x_i^D} + E_{x_k^A}} \times$$
$$\times\left(\sum_{i=1}^{k}\left(C_r(D_{x_i^{cw}}, D_{x_i^{ccw}})E_{x_i^D}\right) + C_r(A_{x_k^{cw}}, A_{x_k^{ccw}})E_{x_k^A}\right), \quad (4)$$

$$\gamma_y = -\frac{1}{\sum_{i=1}^{k} E_{y_i^D} + E_{y_k^A}} \times$$
$$\times\left(\sum_{i=1}^{k}\left(C_r(D_{y_i^{cw}}, D_{y_i^{ccw}})E_{y_i^D}\right) + C_r(A_{y_k^{cw}}, A_{y_k^{ccw}})E_{y_k^A}\right). \quad (5)$$

The weighting factors applied in the equations above are defined by (6)–(9):

$$E_{x_i^D} = \sum_{n=0}^{J-1}\left(D^R_{x_i^{cw}}[n]^2 + D^R_{x_i^{ccw}}[n]^2\right), \quad (6)$$

$$E_{y_i^D} = \sum_{n=0}^{J-1}\left(D^R_{y_i^{cw}}[n]^2 + D^R_{y_i^{ccw}}[n]^2\right), \quad (7)$$

$$E_{x_k^A} = \sum_{n=0}^{J-1}\left(A^R_{x_k^{cw}}[n]^2 + A^R_{x_k^{ccw}}[n]^2\right), \quad (8)$$

$$E_{y_k^A} = \sum_{n=0}^{J-1}\left(A^R_{y_k^{cw}}[n]^2 + A^R_{y_k^{ccw}}[n]^2\right), \quad (9)$$

where $D^R_{x_i^{cw}}$, $D^R_{y_i^{cw}}$, $D^R_{x_i^{ccw}}$, $D^R_{y_i^{ccw}}$ constitute the reconstructed signals of length J, corresponding to the correlated detail (D) coefficients on a given level (i) of the discrete wavelet decomposition carried out individually for the x and y components of the clockwise (*cw*) and counter-clockwise (*ccw*) follow-up trajectories, whereas $A^R_{x_k^{cw}}$, $A^R_{y_k^{cw}}$, $A^R_{x_k^{ccw}}$, $A^R_{y_k^{ccw}}$ represent the reconstructed signals of length J, corresponding to the correlated approximation (A) coefficients only at the last level (k) of the decomposition. The weights $E_{x_i^D}$, $E_{y_i^D}$, $E_{x_k^A}$, $E_{y_k^A}$ constitute the sums of energies of the reconstructed signals corresponding to the correlated wavelet coefficients.

The quantities γ_x, γ_y assume values in the range of [-1,1], where 1 represents the maximum dynamic symmetry of posture and -1 is identified with the maximum anti-symmetry thereof, *i.e.* correlated coefficients series are in perfect phase opposition to each other. To simplify the obtained two-dimensional representation of symmetry, a new coefficient was established (10)

$$\gamma = 1 - \left|\vec{d}\right| \Big/ 2\sqrt{2}, \quad (10)$$

where

$$\left|\vec{d}\right| = \sqrt{\left(1-\gamma_x\right)^2 + \left(1-\gamma_y\right)^2}. \quad (11)$$

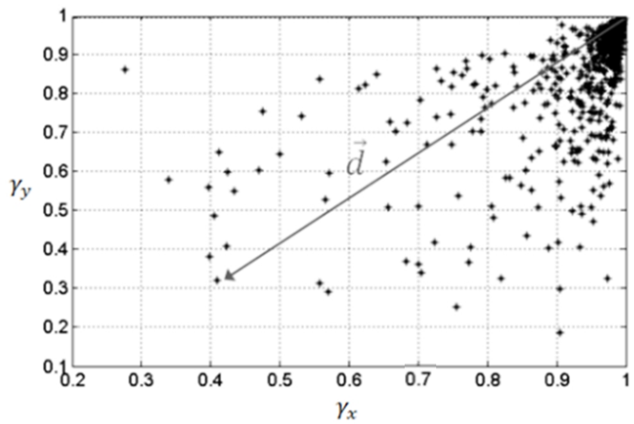


Fig. 4. Visualisation of the distance vector $\vec{d}$ based on which the γ coefficient is calculated.

The newly established symmetry coefficient quantifies the vector distance of the point (γ_x,γ_y) from the point representing the ideal symmetry of postural dynamics (Fig. 4), namely the point (1,1). The values assumed by γ are in the range [0,1], where 1 represents the maximum symmetry of postural dynamics whereas 0 is identified with the maximum anti-symmetry thereof. This new measure of postural symmetry enables simple quantification of the performance of the human balance system while the subject is performing deterministically stimulated activities. The use of the wavelet coefficients obtained as the result of the discrete wavelet decomposition allows for correlational signal analysis in a series of dyadically arranged frequency bands, with emphasized wavelet-like patterns in the wavelet coefficient domains at all levels of the decomposition. The shapes of the utilized db2 mother wavelet and its corresponding scaling function reflect the behaviour of the follow-up trajectory's tracking nature. Besides, they are very simple to implement – only four coefficients for each of the filters in a single decomposition stage. These were the main qualities behind the decision to use the db2 wavelet.

III. EXPERIMENTS

Applicability of the proposed method was verified in the group of 30 patients rehabilitated after total hip arthroplasty, comprised of 19 women (aged 41 years–75 years) and 11 men (aged 37 years–76 years). The average age of patients in the whole group was 61.43 years (*std* = 9.01 years).

Figure 5 presents the values of the newly proposed postural symmetry measure obtained for a sample patient over the course of the rehabilitation program.

Figure 6 presents the bar plot showing the values of the γ coefficient calculated at the beginning as well as the end of the rehabilitation program. The progress in the symmetry of postural dynamics was observed in all 30 patients. Statistical significance of differences in values obtained at the beginning and the end of the rehabilitation program was confirmed using sign test: $Z = -5.295$; $p < 0.0001$ ($p = 1.924E-7$). The sign test was used as the distribution of differences between the paired observations was neither normal nor symmetrical.

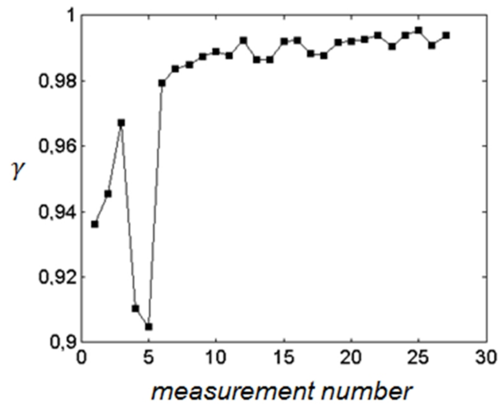


Fig. 5. The values of the proposed postural symmetry measure obtained for a sample patient over the course of the rehabilitation program.

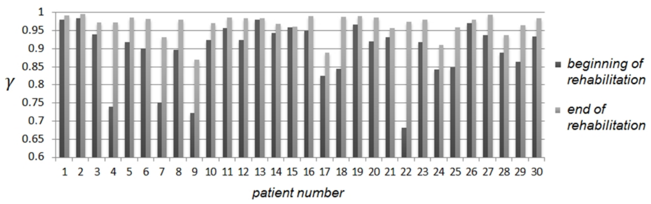


Fig. 6. The values of the proposed postural symmetry measure γ obtained at the beginning and end of the rehabilitation program of 30 patients who underwent total hip arthroplasty.

Similar analysis was conducted for postural symmetry measures obtained in static posturography, performed before each of the follow-up posturographic examinations, expressed by the coefficients ΔS_M, ΔS_{AT}, ΔS_{LT}, ΔS_{DT} quantifying, respectively, the relative loading of the limbs, relative area under the unrolled CoP trajectory, relative length of the trajectory, and the relative deviation from the centre of the trajectory. Statistically significant difference between the values obtained at the beginning and end of the rehabilitation program was confirmed for the relative limb loading coefficient (ΔS_M) using t-test for dependent variables ($p = 1.3627E-7$). In case of ΔS_{AT}, ΔS_{LT}, ΔS_{DT}, testing of significance of the difference between the coefficient values obtained at the beginning and end of the rehabilitation, due to the lack of normality and symmetry of the distributions, was conducted using the sign test. The results, however, did not confirm statistical significance of changes in the values of these coefficients (ΔS_{AT}: $p = 0.213$; ΔS_{LT}: $p = 0.404$; ΔS_{DT}: $p = 0.142$). This somewhat proves the inefficiency of the commonly utilized posturographic measures of postural symmetry in evaluation of patients rehabilitated after total hip arthroplasty and motivates the development of new measures based on the follow-up posturography diagnostics.

To evaluate the relations between the proposed measure of symmetry and the measures commonly applied in static posturography, a number of Spearman correlation coefficients were calculated. Table I and Table II present the values of these coefficients obtained at the beginning as well as the end of the rehabilitation program. It is evident that there are no significant correlations between γ and other measures of postural symmetry. Significant correlations are observed only in the group of symmetry measures used in static posturography.

TABLE I. SPEARMAN'S CORRELATION COEFFICIENTS OBTAINED FOR γ, ΔS_M, ΔS_{AT}, ΔS_{LT}, ΔS_{DT} MEASURES AT THE BEGINNING OF THE REHABILITATION PROGRAM AFTER TOTAL HIP ARTHROPLASTY (VALUES IN BOLD ARE STATISTICALLY SIGNIFICANT).

	γ	ΔS_M	ΔS_{AT}	ΔS_{LT}	ΔS_{DT}
γ	1	-0.036	-0.079	-0.220	0.014
ΔS_M	-0.036	1	0.274	0.183	**0.410**
ΔS_{AT}	-0.079	0.274	1	**0.808**	**0.777**
ΔS_{LT}	-0.220	0.183	**0.808**	1	**0.661**
ΔS_{DT}	0.014	**0.410**	**0.777**	**0.661**	1

TABLE II. SPEARMAN'S CORRELATION COEFFICIENTS OBTAINED FOR γ, ΔS_M, ΔS_{AT}, ΔS_{LT}, ΔS_{DT} MEASURES AT THE END OF THE REHABILITATION PROGRAM AFTER TOTAL HIP ARTHROPLASTY (VALUES IN BOLD ARE STATISTICALLY SIGNIFICANT).

	γ	ΔS_M	ΔS_{AT}	ΔS_{LT}	ΔS_{DT}
γ	1	0.064	-0.034	-0.120	-0.218
ΔS_M	0.064	1	0.032	-0.009	0.047
ΔS_{AT}	-0.034	0.032	1	**0.771**	**0.676**
ΔS_{LT}	-0.120	-0.009	**0.771**	1	**0.471**
ΔS_{DT}	-0.218	0.047	**0.676**	**0.471**	1

It is legitimate to assume that γ quantifies different aspects of postural symmetry, what proves its diagnostic value.

IV. CONCLUSIONS

The study confirmed applicability of the herein presented postural symmetry evaluation method in the rehabilitation of patients who underwent total hip arthroplasty. The obtained results indicate that the γ measure quantifies certain aspects of postural symmetry which are not detectable using typical static posturography coefficients.

The major advantage of the method is the capability to perform dynamic postural symmetry assessment using low-cost, single-plate static posturography platform.

The main goal of further studies will be evaluation of the applicability of the proposed method in diagnostics of patients affected with other health issues, *e.g.* Parkinson's disease.

REFERENCES

[1] H. Chaudhry, B. Bukiet, Z. Ji, T. Findley, "Measurement of balance in computer posturography. Comparison of methods – A brief review", *Journal of Bodywork & Movement Therapies*, vol. 15, no. 4, pp. 82–91, 2011. [Online]. Available: http://dx.doi.org/10.1016/j.jbmt.2008.03.003

[2] M. Duarte, S. M. S. F. Freitas, "Revision of posturography based on force plate for balance evaluation", *Rev Bras Fisioter*, vol. 14, no. 3, pp. 183–92, 2010. [Online]. Available: http://dx.doi.org/10.1590/S1413-35552010000300003

[3] Z. Kidoń, K. Pethe-Kania, D. Kania, "Stabilography platform using for progress estimation in rehabilitation of patients after a hip replacement surgery", *PAK,* vol. 54, no. 2, pp. 71–75, 2008. (in Polish).

[4] T. Łukaszewicz, D. Kania, Z. Kidoń, K. Pethe-Kania, "Posturographic methods for body posture symmetry assessment", *Bulletin of the Polish Academy of Sciences Technical Sciences*, vol. 63, no. 4, 2015. [Online]. Available: http://dx.doi.org/10.1515/bpasts-2015-0103

[5] K. Pethe-Kania, "Stabilography in the rehabilitation of patients after a hip replacement arthroplasty", PhD dissertation, Śląski Uniwersytet Medyczny w Katowicach Wydział Lekarski w Katowicach, 2011 (in Polish).

[6] P. M. da Silva Schmidt, A. Marques Giordani, A. G. Rossi, P. L. Coser, "Balance assessment in alcoholic subjects", *Braz J Otorhinolaryngol*., vol. 76, no. 2, pp. 148–55, 2010.

[7] T. Łukaszewicz, Z. Kidoń, D. Kania, K. Pethe-Kania, "Postural symmetry evaluation using bilateral and rotational symmetry degrees calculated for stabilographic trajectories", *Przeglad Elektrotechniczny,* no. 7, pp. 197–201, 2013. (in Polish)

[8] T. Łukaszewicz, Z. Kidoń, D. Kania, K. Pethe-Kania, "Postural symmetry assessment based on the analysis of trajectories measured during the follow-up posturography examination", *Electronics – Constructions, Technologies, Applications*, vol. 55, no. 1, pp. 51–54, 2014. (in Polish)

[9] G. Strang, T. Nguyen, *Wavelets and Filter Banks*. Cambridge, MA: *Wellesley-Cambridge*, 1996.

[10] A. H. Najmi, *Wavelets: A Concise Guide*. The John Hopkins University Press, 2012.

[11] M. Vetterli, J. Kovačević, *Wavelets and Subband Coding*. Englewood Cliffs, NJ: Prentice-Hall, 1995.