IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received December 30, 2018, accepted January 15, 2019, date of publication January 31, 2019, date of current version March 12, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2895765

Postural Symmetry Evaluation Based on the Analysis of Temporary and Average CoP Displacements Registered During the Follow-Up Posturography

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This work was supported by the Polish Ministry of Science and Higher Education.

ABSTRACT This paper presents a method enabling a postural symmetry assessment based on the evaluation of similarity of temporary and average CoP (Center of Pressure) displacements registered in response to the clockwise and counter-clockwise visual stimuli applied while performing the so-called follow-up posturography. This kind of visual feedback diagnostics is an intermediary between the static posturography and the dynamic posturography. One of its advantages is the ability to evaluate the dynamic performance of the human balance and posture control mechanisms using relatively inexpensive and popular static posturography platforms. The method presented in this paper was developed as a means for measuring the effectiveness of the rehabilitation program following total hip arthroplasty. The postural symmetry is, in this case, evaluated as the degree of mutual symmetry of the visually stimulated loading exerted on the left and right lower limbs. Usability of the method was verified in the group of 30 patients rehabilitated after total hip arthroplasty. The statistical analysis confirmed a significant growth of the values of the proposed symmetry measure over the period of the 21-day rehabilitation program ($p < 0.001$). There were, however, no significant correlations between that measure and the symmetry measures applied in the case of static posturography. The obtained results support the statement that the herein presented diagnostic approach enables the quantification of some other aspects of postural symmetry, namely the dynamic ones. This also corroborates the diagnostic value of the method discussed in this paper.

INDEX TERMS postural symmetry evaluation, posturography, the follow-up posturography, biomedical signal processing, total hip arthroplasty.

I. INTRODUCTION

Posturography is a diagnostic method enabling assessment of the human body's ability to maintain biomechanical balance [1]–[5]. Health evaluation techniques utilizing this kind of approach are based on the analysis of the so-called posturographic trajectories (fig. 1) reflecting temporary positions of the CoP (Center of Pressure), which is the point of application of the net reaction force of the examined subject's support surface. The devices used for acquisition of such signals are called posturographic platforms.

The associate editor coordinating the review of this manuscript and approving it for publication was Remigiusz Wisniewski.

Posturographic health evaluation is carried out using selected measures quantifying particular features of the CoP trajectories, e.g. length of the CoP trajectory [6]. As far as the study discussed in this article is concerned, posturography was utilized to monitor the process of rehabilitation of patients who underwent total hip arthroplasty [6], [7]. For such patients fast restoration of a proper body posture, involving mutual symmetrization of loading exerted on the left and right hip joints, is a priority.

Coefficients calculated using data acquired with posturographic platforms can be valuable sources of information about the status of motoric functions of the human body. This information can be used to evaluate the efficacy of

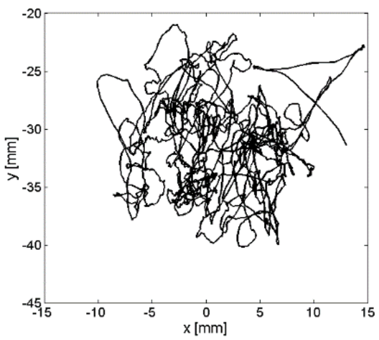

FIGURE 1. An example of the CoP trajectory registered during a static posturography examination.

treatment of certain maladies or abnormalities, what in turn can expedite the adaptation of the applied therapies to the current health state of an individual patient. The authors of this article are particularly interested in posturographic evaluation of the mutual lower limb loading symmetry in patients rehabilitated after total hip arthroplasty.

The simplest way to assess the degree of mutual symmetry of loading exerted on the lower limbs is to measure and compare the average weights carried by each of the limbs. This kind of assessment can be realized as part of a standard posturography, known as the static posturography, performed on a single double-plate posturographic platform or two single-plate ones [6]. It's a refinement to a simple diagnostic method known in medical communities as the test of two scales [8]. With simplicity of this method, however, comes also its fundamental flaw. Namely, the averaging of loading carried by the lower limbs translates into a loss of information on the dynamics of the CoP displacements [6].

Another relatively simple way to assess mutual limb loading symmetry boils down to the comparison of the coefficients quantifying the CoP trajectories obtained independently (yet simultaneously) for the left and right lower limbs [6], [7]. Such coefficients evaluate certain features of the CoP trajectories, e.g. the length of the trajectory, its area or the average CoP deviation from the center of the trajectory. As these coefficients are typically assessed during a standard static posturography, the examined patients are not being externally stimulated while performing the diagnostics (at least not intentionally). It's worth to point out that the data obtained in this type of examination allows only for highly generalized conclusions regarding the actual health state of the examined subject.

Clinical experiences have shown that the CoP trajectories registered in response to certain mutually symmetrical visual stimuli would be a more valuable source of diagnostic information – especially in case of patients rehabilitated after total hip arthroplasty [6], [7]. Such stimuli are applied in the so-called follow-up posturography.

There are three main types of posturography: static posturography, dynamic posturography and visual feedback posturograpy. The first one, as it has already been stated, is characterized by a lack of external stimulation. During such a diagnostics the subject is standing on a posturographic platform in an upright position, having his/her eyes open or closed [7].

In the dynamic posturography both mechanical and visual stimuli are applied. The subject's biomechanical stability is perturbed via rotation/translation of the support plane or tilting of the cabin surrounding the platform [9], [10]. This enables evaluation of an examined person's responses in conditions similar to the ones met in daily life. It's worth to note, however, that the equipment utilized in this kind of diagnostics is much more expensive than the one used in a typical static posturography examination.

The third type of posturography, the visual feedback posturography, is an intermediary between the static and dynamic approaches – it implements visual stimulation and can be realized resorting to the equipment used in static posturography [6].

The follow-up posturography, being at the core of the study discussed in this article, is a subtype of visual feedback posturography. In this type of diagnostics the subject is supposed to sway his or her body in such a way that the CoP trajectory's marker, presented on the computer screen, coincides with the marker of the visual stimulus [6]. The marker of the visual stimulus moves with a constant speed in a circular fashion, first clockwise and then counter-clockwise – a single circle is drawn in both directions. The applied visual stimuli are mutually symmetrical against the y-axis. It's worth to mention that the amplitude of the expected body swaying is adjusted to the swaying abilities of a given patient [6]. Prior to the actual follow-up posturography examination, the patient is asked to lean forward and backward as much as possible, without losing his/her balance. Results of this procedure determine amplification level of the excursions of the CoP marker presented on the computer screen. Fig. 2 shows the examples of the clockwise and counter-clockwise CoP trajectories together with their corresponding visual stimuli.

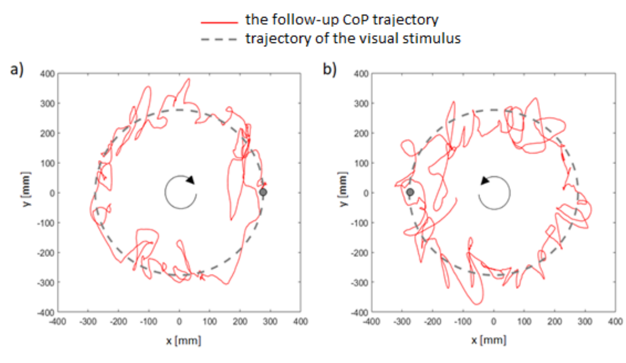

FIGURE 2. Trajectory of the clockwise (a) and counter-clockwise (b) visual stimuli with corresponding sample follow-up CoP trajectories [6].

The aim of this paper is to present a method for postural symmetry evaluation, quantifying similarity of loading of the lower limbs in terms of temporary and average CoP displacements registered in response to the clockwise and counter-clockwise visual stimuli applied in the follow-up posturography. Evaluation of symmetry in terms of temporary CoP displacements is performed using covariance-based coefficients calculated independently for the lateral and sagittal coordinates of the follow-up CoP trajectories. The average CoP displacements are quantified using the so-called half-plane averaging of these trajectories. The main advantage of the herein presented approach is the ability to assess mutual symmetry of externally stimulated loading of the lower limbs, using single-plate posturographic platform. This kind of diagnostics gives an opportunity to evaluate dynamic performance of the human balance and posture control mechanisms using relatively inexpensive and popular measurement platforms designed for static posturography.

The following sections present theoretical background concerning posturographic measures of postural symmetry, the details of postural symmetry evaluation method based on the analysis of temporary and average CoP displacements registered during the follow-up posturography, results of the experiments and final conclusions of the conducted research.

II. THEORETICAL BACKGROUND

Posturography is typically used to evaluate the health status of patients suffering from musculoskeletal and neurological disorders, e.g. victims of accidents [11], [12], hemiparetic patients [13], people with cerebellar diseases [14], [15], Parkinson's disease [16]–[18] or disorders within the vestibular system [19]–[21]. The authors of this article, however, concentrate on its uses in the context of postural symmetry assessment of patients undergoing rehabilitation after total hip arthroplasty.

Posturographic assessment of postural symmetry can naturally be realized via comparative analysis of the CoP trajectories registered simultaneously for the left (CoP_L) and right (CoP_R) lower limbs, using a single double-plate posturographic platform or two single-plate ones. An important advantage of the method presented in this paper is that the postural symmetry assessment can be realized using just one single-plate platform. In this case the CoP trajectory is referred to as the central CoP trajectory (CoP_C). Such a signal may also be obtained from trajectories registered individually (and simultaneously) for the left (CoP_L) and right (CoP_R) lower limbs.

For the purposes of the study discussed in this paper, double-plate posturographic platform was utilized. The device was designed and built at the Silesian University of Technology in Gliwice, Poland [6]. Its measurement resolutions corresponding to the x and y coordinates of the central CoP trajectories (CoP_C), with respect to the examined subjec's body mass, are presented in figures 3 and 4, respectively. The figures were obtained assuming that the weights acting on the left and right plates of the platform were equal. It was also assumed that the individual CoPs (CoP_R, CoP_L) were centrally applied with respect to each plate [6]. In order to determine the coordinates of the CoP points corresponding to each of the lower limbs, the downward forces acting on the posturographic platform have to be measured in at least 6 positions ($P_i(x_i, y_i)$; $i = 1\ldots6$). This task is achieved using a set of strain gauge transducers deployed in the points whose (x, y) coordinates are precisely determined (fig. 5). After deriving the coordinates of the CoP individually for the left and right lower limbs, one can also calculate the CoP of the central trajectory (CoP_C).

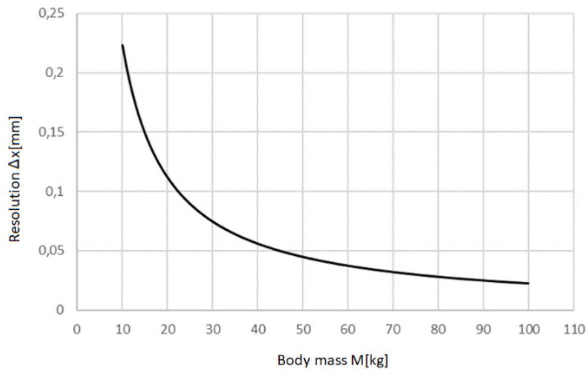

FIGURE 3. Measurement resolution for the x coordinate of the CoP_C as a function of the examined subject's body mass [6].

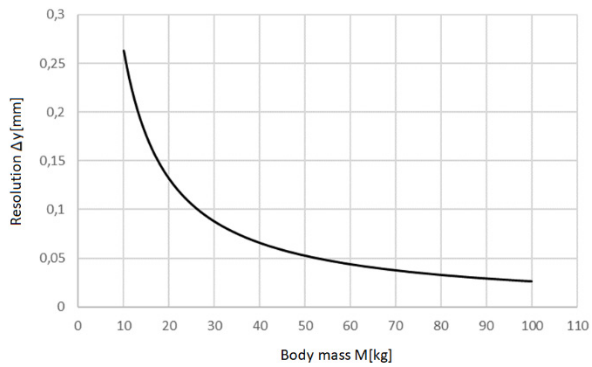

FIGURE 4. Measurement resolution for the y coordinate of the CoP_C as a function of the examined subject's body mass [6].

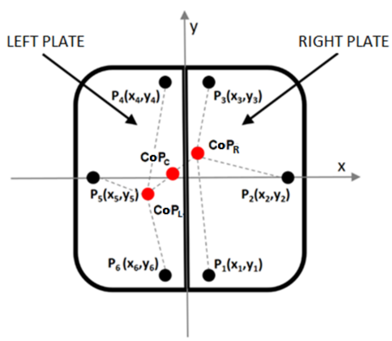

FIGURE 5. Illustration of the utilized double-plate posturographic platform, showing the way in which coordinates of the CoP_L (X_L, Y_L), CoP_R (X_R, Y_R) and CoP_C (X_C, Y_C) are derived, where P1-P6 represent the points at which the strain gauge transducers were deployed [6].

Measurement of the downward forces acting on each of the strain gauge transducers enables assessment of the net downward forces exerted individually on the left and right plates of the platform, providing the data needed to calculate average lower limb loading coefficients. To make such calculations for the case presented in fig. 5, the following formulas can be applied [2], [6]:

$$P_L(i) = \sum_{j=4}^{6} P_j(i), \quad P_R(i) = \sum_{j=1}^{3} P_j(i) \tag{1}$$

where: j – index of the j-th strain gauge transducer, i – time of the measurement, $P_j(i)$ – force acting on the j-th transducer; $P_R(i)$, $P_L(i)$– net downward forces exerted on the right and left plates of the posturographic platform, respectively.

The average limb loading coefficients are calculated through averaging of $P_R(i)$ and $P_L(i)$ over N samples of the acquired signals [2], [6]:

$$W_L = \frac{\sum_{i=1}^{N} P_L(i)}{N}, \quad W_R = \frac{\sum_{i=1}^{N} P_R(i)}{N} \tag{2}$$

Knowing the coordinates of the CoP at subsequent moments in time enables computation of a variety of posturographic coefficients, e.g. the length of the CoP trajectory (LT), the average CoP deviation from the trajectory's center (DT) and the area under the unrolled trajectory (AT), which is the sum of the areas of all triangles comprised of two consecutive points of the CoP trajectory and the middle point of the (x, y) coordinate system [2], [6], [7].

Postural symmetry can be assessed calculating the difference of values of a given coefficient obtained in static posturography individually for the left and right lower limbs. Unfortunately, this simple approach gives highly personalized results, unreliable for inter-patient comparisons. Problems may also arise in case of intra-patient observations carried out over prolonged periods of time. For this reason it is better to apply the relative measures of postural symmetry, expressed by the following general formulas [2], [6]:

$$S_\psi = \frac{\psi_{L|R}}{\psi_L + \psi_R}, \quad S_\psi \in [0, 1] \tag{3}$$

$$S_{\Delta\psi} = \frac{\psi_L - \psi_R}{\psi_L + \psi_R}, \quad S_{\Delta\psi} \in [-0.5, 0.5] \tag{4}$$

$$S_{|\Delta\psi|} = \frac{|\psi_L - \psi_R|}{\psi_L + \psi_R} = \left|2S_\psi - 1\right|, \quad S_{|\Delta\psi|} \in [0, 1] \tag{5}$$

$$S_{i_{|\Delta\psi|}} = 1 - S_{|\Delta\psi|}, \quad S_{i_{|\Delta\psi|}} \in [0, 1] \tag{6}$$

where: ψ_L, ψ_R, $\psi_{L|R}$ – absolute coefficients obtained while performing posturographic examination (e.g. length of the CoP trajectory), corresponding to the left limb (ψ_L), right limb (ψ_R) and the limb for which the given measure is computed ($\psi_{L|R}$), respectively.

The abovementioned relative postural symmetry measures minimize dispersion of the absolute measures, normalizing the way in which the differences in loading of the left and right lower limbs are expressed. For example, the S_ψ measure assumes values from within the range of [0, 1]. For a perfect limb loading symmetry the value of S_ψ would be equal to 0.5. The magnitude of deviation from this ideal condition indicates the level of the limb loading asymmetry. In case of $S_{\Delta\psi}$ the range of possible values is limited to [−0.5, 0.5], where 0 is identified with the state of ideal postural symmetry, whereas −0.5 and 0.5 correspond to the extremes in postural asymmetry. The values of $S_{|\Delta\psi|}$ are contained in [0, 1], where 0 represents the ideal postural symmetry and 1 characterizes the total lack thereof. For $S_{i_{|\Delta\psi|}}$ the range of possible values is the same as in case of $S_{|\Delta\psi|}$, however, this time 0 and 1 have opposite meanings.

Below is the list of the relative postural symmetry measures applied in the study discussed in this article [6]:

$$S_{i_{|\Delta W|}} = 1 - \left|2\frac{W_{L|R}}{W_L + W_R} - 1\right| \tag{7}$$

$$S_{i_{|\Delta LT|}} = 1 - \left|2\frac{LT_{L|R}}{LT_L + LT_R} - 1\right| \tag{8}$$

$$S_{i_{|\Delta AT|}} = 1 - \left|2\frac{AT_{L|R}}{AT_L + AT_R} - 1\right| \tag{9}$$

$$S_{i_{|\Delta DT|}} = 1 - \left|2\frac{DT_{L|R}}{DT_L + DT_R} - 1\right| \tag{10}$$

where: W– average loading of the lower limb, LT – length of the CoP trajectory, DT– average CoP deviation from the trajectory's center, AT– area under the unrolled CoP trajectory [2].

Posturographic measures for postural symmetry assessment are currently based mainly on the quantification of the CoP trajectories registered in static posturography. This kind of evaluation, however, provides information only about the static loading of the lower limbs. The next section of this article presents a method enabling postural symmetry assessment based on the analysis of the follow-up CoP trajectories. The obtained postural symmetry measure γ quantifies mutual symmetry of the visually stimulated loading of the lower limbs, both in terms of average and temporary CoP displacements.

III. POSTURAL SYMMETRY EVALUATION BASED ON THE ANALYSIS OF TEMPORARY AND AVERAGE COP DISPLACEMENTS REGISTERED DURING THE FOLLOW-UP POSTUROGPRAHY

A. GENERAL CONCEPT

The measure of postural symmetry presented in this section evaluates similarity of the counter-clockwise follow-up posturographic trajectory and the mirror image against the y-axis of the clockwise follow-up posturographic trajectory, in terms of temporary and average CoP displacements [6]. The first of the considered aspects of postural symmetry is examined using covariance-based coefficients calculated independently for the corresponding coordinates of both trajectories. In order to evaluate the symmetry of posture in terms of average CoP displacements, the so-called half-plane averaging coefficients are used. It is worth to emphasize that the herein presented postural symmetry evaluation method relies on the fact that mutual symmetry of the applied clockwise and counter-clockwise visual stimuli makes the subject to sway attempting to exert mutually symmetrical loading on the lower limbs – the degree of postural symmetry depends on mutual symmetry of the swaying observed from the perspective of the left and right lower limbs.

B. POSTURAL SYMMETRY ASSESSMENT USING COVARIANCE COEFFICIENTS CALCULATED FOR THE CORRESPONDING COORDINATES OF THE FOLLOW-UP COP TRAJECTORIES

Evaluation of postural symmetry in terms of temporary displacements of the CoP can be realized using properly scaled covariance coefficients calculated independently for the corresponding x and y coordinates of the counter-clockwise follow-up CoP trajectory and the mirror image against the y-axis of the clockwise follow-up CoP trajectory. The following formula depicts the applied scaled covariance coefficient for the lateral signal components [6]:

$$\rho_{X_{ccw}X'_{cw}} = \frac{R_{X_{ccw}X'_{cw}}}{R_{X'_{cw}X'_{cw}}} \tag{11}$$

where:

- $R_{X_{ccw}X'_{cw}}$ – covariance of the lateral coordinates of the counter-clockwise follow-up CoP trajectory and the mirror image against the y-axis of the clockwise follow-up CoP trajectory;
- $R_{X'_{cw}X'_{cw}}$ – variance of the lateral coordinates of the mirror image against the y-axis of the clockwise follow-up CoP trajectory.

In a similar way the scaled covariance coefficient for the sagittal signal components was defined [6]:

$$\rho_{Y_{ccw}Y'_{cw}} = \frac{R_{Y_{ccw}Y'_{cw}}}{R_{Y'_{cw}Y'_{cw}}} \tag{12}$$

where:

- $R_{Y_{ccw}Y'_{cw}}$ – covariance of the sagittal coordinates of the counter-clockwise follow-up CoP trajectory and the mirror image against the y-axis of the clockwise follow-up CoP trajectory;
- $R_{Y'_{cw}Y'_{cw}}$ – variance of the sagittal coordinates of the mirror image against the y-axis of the clockwise follow-up CoP trajectory.

Values achieved by $\rho_{X_{ccw}X'_{cw}}$ and $\rho_{Y_{ccw}Y'_{cw}}$ belong to a set of real numbers. In order to narrow down the range of possible results as well as to simplify their interpretation, the following measures have been derived [6]:

$$\vartheta_{X_{ccw}X'_{cw}} = \begin{cases} 0 & for\ \rho_{X_{ccw}X'_{cw}} = 0 \\ min\left\{\rho_{X_{ccw}X'_{cw}}, \frac{1}{\rho_{X_{ccw}X'_{cw}}}\right\} & for\ \rho_{X_{ccw}X'_{cw}} > 0 \\ max\left\{\rho_{X_{ccw}X'_{cw}}, \frac{1}{\rho_{X_{ccw}X'_{cw}}}\right\} & for\ \rho_{X_{ccw}X'_{cw}} < 0 \end{cases} \tag{13}$$

$$\vartheta_{Y_{ccw}Y'_{cw}} = \begin{cases} 0 & for\ \rho_{Y_{ccw}Y'_{cw}} = 0 \\ min\left\{\rho_{Y_{ccw}Y'_{cw}}, \frac{1}{\rho_{Y_{ccw}Y'_{cw}}}\right\} & for\ \rho_{Y_{ccw}Y'_{cw}} > 0 \\ max\left\{\rho_{Y_{ccw}Y'_{cw}}, \frac{1}{\rho_{Y_{ccw}Y'_{cw}}}\right\} & for\ \rho_{Y_{ccw}Y'_{cw}} < 0 \end{cases} \tag{14}$$

The values of $\vartheta_{X_{ccw}X'_{cw}}$ and $\vartheta_{Y_{ccw}Y'_{cw}}$ are contained in the interval $[-1, 1]$, where -1 represents the condition in which one of the considered signals is a π [rad] shifted version of the second signal, whereas 1 identifies the condition in which the signals are mutually compliant both in phase and amplitude. The extreme values of -1 and 1 characterize the cases of ideal postural antisymmetry and the ideal postural symmetry, respectively.

To represent the degree of postural symmetry in terms of temporary CoP displacements both in the lateral and sagittal planes, a new coefficient quantifying the length of a vector anchored in the point (1,1), identified with ideal postural symmetry, and terminated in the point $(\vartheta_{X_{ccw}X'_{cw}}, \vartheta_{Y_{ccw}Y'_{cw}})$, has been established [6]:

$$\vartheta = 1 - \frac{\sqrt{\left(\vartheta_{X_{ccw}X'_{cw}} - 1\right)^2 + \left(\vartheta_{Y_{ccw}Y'_{cw}} - 1\right)^2}}{2\sqrt{2}} \tag{15}$$

Values of ϑ are limited to the unit interval $[0, 1]$, where 0 and 1 represent the ideal postural antisymmetry and the ideal postural symmetry, respectively.

C. POSTURAL SYMMETRY ASSESSMENT WITH HALF-PLANE AVERAGING OF THE FOLLOW-UP COP TRAJECTORIES

The ϑ coefficient presented in the previous section quantifies postural symmetry only in terms of temporary displacements of the CoP. It does not take into account the average loading of the lower limbs. In order to evaluate also this aspect of postural symmetry, a series of coefficients $\varphi_{X_{cw}}$, $\varphi_{X_{ccw}}$, $\varphi_{Y_{cw}}$ and $\varphi_{Y_{ccw}}$ has been established. The first two of them ($\varphi_{X_{cw}}, \varphi_{X_{ccw}}$) quantify symmetry of the average CoP displacements against the y-axis, individually for the clockwise (cw) and counter-clockwise (ccw) follow-up CoP trajectories, whereas $\varphi_{Y_{cw}}$ and $\varphi_{Y_{ccw}}$ evaluate it against the x-axis. The $\varphi_{X_{cw}}$ coefficient is defined with the following formula [6]:

$$\varphi_{X_{cw}} = \begin{cases} \frac{N_{X_{Lcw}}|X_{Lcw}|}{N_{X_{Lcw}}|X_{Lcw}| + N_{X_{Rcw}}X_{Rcw}} & for\ N_{X_{Lcw}}, N_{X_{Rcw}} \in Z_+ \\ 0 \quad for\ N_{X_{Lcw}} = 0\ and\ N_{X_{Rcw}} \in Z_+ \\ 1 \quad for\ N_{X_{Lcw}} \in Z_+\ and\ N_{X_{Rcw}} = 0 \\ 0.5 \quad for\ N_{X_{Lcw}} = 0\ and\ N_{X_{Rcw}} = 0 \end{cases} \tag{16}$$

where:

- X_{Lcw} – the arithmetic mean of the x-coordinates of the points comprising the clockwise follow-up CoP trajectory, located on the left side of the y-axis;
- X_{Rcw} – the arithmetic mean of the x-coordinates of the points comprising the clockwise follow-up CoP trajectory, located on the right side of the y-axis;

- $NX_{L_{cw}}$ – the number of points comprising the clockwise follow-up CoP trajectory, located on the left side of the y-axis;
- $NX_{R_{cw}}$ –the number of points comprising the clockwise follow-up CoP trajectory, located on the right side of the y-axis.

Definition of φX_{ccw} is analogous to the definition of φX_{cw}, however in this case the distribution of the CoP displacements is calculated for the counter-clockwise follow-up CoP trajectory and the ratio expressing the degree of average CoP displacement is evaluated for the points located on the right side of the y-axis [6]:

$$\varphi X_{ccw}=\begin{cases}\frac{NX_{R_{ccw}}X_{R_{ccw}}}{NX_{L_{ccw}}|X_{L_{ccw}}|+NX_{R_{ccw}}X_{R_{ccw}}} & for\ NX_{R_{ccw}}, NX_{L_{ccw}} \in Z_{+}\\ 0 \quad for\ NX_{R_{ccw}}=0\ and\ NX_{L_{ccw}} \in Z_{+} & \\ 1 \quad for\ NX_{R_{ccw}} \in Z_{+}\ and\ NX_{L_{ccw}}=0 & \\ 0.5 \quad for\ NX_{R_{ccw}}=0\ and\ NX_{L_{ccw}}=0 & \end{cases} \tag{17}$$

where:

- $X_{R_{ccw}}$ – the arithmetic mean of the x-coordinates of the points comprising the counter-clockwise follow-up CoP trajectory, located on the right side of the y-axis;
- $X_{L_{ccw}}$ – the arithmetic mean of the x-coordinates of the points comprising the counter-clockwise follow-up CoP trajectory, located on the left side of the y-axis;
- $NX_{R_{ccw}}$ – the number of points comprising the counter-clockwise follow-up CoP trajectory, located on the right side of the y-axis;
- $NX_{L_{ccw}}$ – the number of points comprising the counter-clockwise follow-up CoP trajectory, located on the left side of the y-axis.

Figure 6 illustrates the halves of the CoP plane which are taken into account when calculating coefficients (16) and (17).

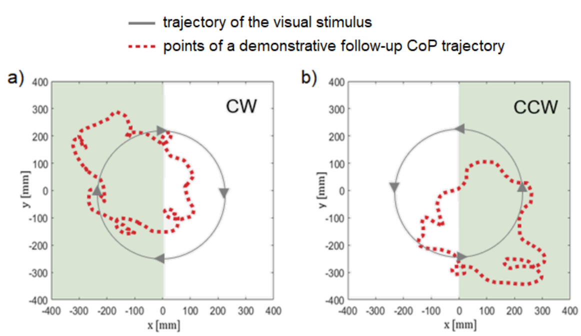

FIGURE 6. Illustrations of the halves of the CoP plane taken into account when calculating coefficients (16) and (17).

The φY_{cw} and φY_{ccw} coefficients are defined in a similar way to φX_{cw} and φX_{ccw}, however, in this case the symmetry is quantified against the x-axis and both ratios expressing the degree of average CoP displacement are evaluated for the points located on the same side of the considered axis [6]:

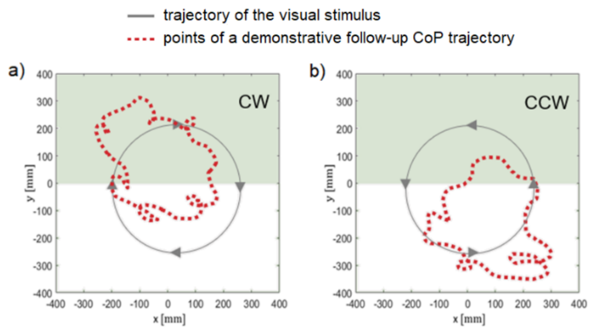

FIGURE 7. Illustrations of the halves of the CoP plane taken into account when calculating coefficients (18) and (19).

$$\varphi Y_{cw}=\begin{cases}\frac{NY_{F_{cw}}Y_{F_{cw}}}{NY_{F_{cw}}Y_{F_{cw}}+NY_{B_{cw}}|Y_{B_{cw}}|} & for\ NY_{F_{cw}}, NY_{B_{cw}} \in Z_{+}\\ 0 \quad for\ NY_{F_{cw}}=0\ and\ NY_{B_{cw}} \in Z_{+} & \\ 1 \quad for\ NY_{F_{cw}} \in Z_{+}\ and\ NY_{B_{cw}}=0 & \\ 0.5 \quad for\ NY_{F_{cw}}=0\ and\ NY_{B_{cw}}=0 & \end{cases} \tag{18}$$

where:

- $Y_{F_{cw}}$ – the arithmetic mean of the y-coordinates of the points comprising the clockwise follow-up CoP trajectory, located above the x-axis;
- $Y_{B_{cw}}$ – the arithmetic mean of the y-coordinates of the points comprising the clockwise follow-up CoP trajectory, located below the x-axis;
- $NY_{F_{cw}}$ – the number of points comprising the clockwise follow-up CoP trajectory, located above the x-axis;
- $NY_{B_{cw}}$ – the number of points comprising the clockwise follow-up CoP trajectory, located below the x-axis.

$$\varphi Y_{ccw}=\begin{cases}\frac{NY_{F_{ccw}}Y_{F_{ccw}}}{NY_{F_{ccw}}Y_{F_{ccw}}+NY_{B_{ccw}}|Y_{B_{ccw}}|} & for\ NY_{F_{ccw}}, NY_{B_{ccw}} \in Z_{+}\\ 0 \quad for\ NY_{F_{ccw}}=0\ and\ NY_{B_{ccw}} \in Z_{+} & \\ 1 \quad for\ NY_{F_{ccw}} \in Z_{+}\ and\ NY_{B_{ccw}}=0 & \\ 0.5 \quad for\ NY_{F_{ccw}}=0\ and\ NY_{B_{ccw}}=0 & \end{cases} \tag{19}$$

where:

- $Y_{F_{ccw}}$ – the arithmetic mean of the y-coordinates of the points comprising the counter-clockwise follow-up CoP trajectory, located above the x-axis;
- $Y_{B_{ccw}}$ – the arithmetic mean of the y-coordinates of the points comprising the counter-clockwise follow-up CoP trajectory, located below the x-axis;
- $NY_{F_{ccw}}$ – the number of points comprising the counter-clockwise follow-up CoP trajectory, located above the x-axis;
- $NY_{B_{ccw}}$ – the number of points comprising the counter-clockwise follow-up CoP trajectory, located below the x-axis.

Figure 7 illustrates the halves of the CoP plane which are taken into account when calculating coefficients (18) and (19).

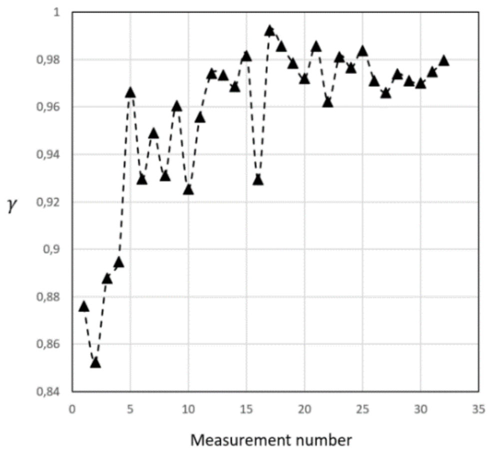

FIGURE 8. Changes in the values of γ observed over the course of the rehabilitation program, obtained for a sample patient after total hip arthroplasty [6].

Based on $\varphi_{X_{cw}}$ and $\varphi_{X_{ccw}}$, the following measure quantifying the mutual lower limbs' loading symmetry in terms of lateral CoP displacements was formulated [6]:

$$\beta_x = 1 - \left|\varphi_{X_{cw}} - \varphi_{X_{ccw}}\right| \tag{20}$$

In a similar way, using $\varphi_{Y_{cw}}$ and $\varphi_{Y_{ccw}}$, the measure of mutual symmetry of the CoP displacements in the sagittal plane was established [6]:

$$\beta_y = 1 - \left|\varphi_{Y_{cw}} - \varphi_{Y_{ccw}}\right| \tag{21}$$

Values achieved by β_x and β_y belong to the unit interval [0, 1], where 0 represents the extreme lack of mutual symmetry in terms of average loading exerted on the left and right lower limbs while the subject is performing visually stimulated swaying movements of his/her body in a given plane, whereas 1 represents the case of ideal symmetry of that loading.

In order to holistically represent the symmetry of posture in terms of the average CoP displacements in both lateral and sagittal planes, a synthetic measure β was defined [6]:

$$\beta = 1 - \sqrt{\frac{(\beta_x - 1)^2 + \left(\beta_y - 1\right)^2}{2}} \tag{22}$$

The above formula represents the normalized length of the vector anchored in the point (1, 1), identified with ideal postural symmetry, and terminated in the point (β_x, β_y). The values of β belong to the unit interval [0, 1], where 0 is indicative of the extreme asymmetry of the average mutual lower limb loading distribution, whereas 1 characterizes the ideal symmetry of that distribution.

D. POSTURAL SYMMETRY ASSESSMENT USING COVARIANCE COEFFICIENTS AND HALF-PLANE AVERAGING OF THE FOLLOW-UP COP TRAJECTORIES

The main idea behind the concepts presented in this article was to define a synthetic measure of postural symmetry enabling quantification of similarity of both temporary and average loadings of the lower limbs, exerted in response to the mutually symmetrical clockwise and counter-clockwise visual stimuli. Analysis of the data acquired during the examinations carried out in the Silesian Center for Rheumatology, Rehabilitation and Disability Prevention in Ustroń, Poland, led to the formulation of the following synthetic postural symmetry coefficient [6]:

$$\gamma = 1 - \sqrt{\frac{(\vartheta - 1)^2 + (\beta - 1)^2}{2}} \tag{23}$$

The above coefficient maps the length of the vector anchored in the point (1,1) and terminated in the point (β, ϑ) into the unit interval [0, 1], where 0 represents the extreme asymmetry of temporary and average mutual lower limb loading distributions, whereas 1 characterizes the ideal symmetry of such distributions. It's worth to note that the point (1,1) is identified with the state of ideal symmetry of posture, whereas (β, ϑ) is determined by the coefficients presented in the previous sections of this paper. The synthetic coefficient γ quantifies postural symmetry in terms of dynamic performance of the human balance and posture control mechanisms. The key advantage of the proposed approach is that it can easily be implemented resorting to a popular and relatively cheap equipment utilized in static posturography.

IV. RESULTS

The usability of the postural symmetry assessment method presented in this article has been verified in the group of 30 patients rehabilitated after total hip arthroplasty [6]. Selection of these patients was preceded by thorough identification of limitations which could have possibly corrupted the obtained results. Selection criteria included patients aged up to 80 years with only one artificial hip joint, having equal legs, and for whom the arthroplasty was carried out due to osteoarthritis [6]. Excluded from the study were individuals with restricted mobility in the other hip joint, knee or ankle joints as well as patients who have experienced severe pain in the joint with endoprosthesis or those who suffered from fixed contractures in any knee or ankle joint [6]. Eliminated from the study were also patients taking psychotropic drugs, hypnotics and those having depression or individuals affected with advanced cancer [6]. The rehabilitation treatment was carried out in a span of 21 days in the Silesian Center for Rheumatology, Rehabilitation and Disability Prevention in Ustroń, Poland. The program involved standard rehabilitation exercises supplemented with postural symmetry training based on the follow-up posturography [6], [7]. The follow-up posturography diagnostics was carried out twice a day, before and after physical rehabilitation exercises [6]. At the beginning and at the end of the rehabilitation program, the static posturography examinations enabling calculation of the following relative postural symmetry measures were also performed: $S_{i_{|\Delta W|}}, S_{i_{|\Delta LT|}}, S_{i_{|\Delta DT|}}, S_{i_{|\Delta AT|}}$. The obtained follow-up CoP trajectories were quantified using the proposed synthetic postural symmetry measure γ. The sign test confirmed

TABLE 1. Spearman's correlation coefficients for $S_{i_{|\Delta W|}}$, $S_{i_{|\Delta LT|}}$, $S_{i_{|\Delta DT|}}$, $S_{i_{|\Delta AT|}}$ and γ at the beginning of the rehabilitation treatment [6].

	$S_{i_{\|\Delta W\|}}$	$S_{i_{\|\Delta DT\|}}$	$S_{i_{\|\Delta AT\|}}$	$S_{i_{\|\Delta LT\|}}$
γ	0.167	0.067	0.218	0.208
$S_{i_{\|\Delta LT\|}}$	0.094	**0.663**	**0.812**	
$S_{i_{\|\Delta AT\|}}$	0.245	**0.761**		
$S_{i_{\|\Delta DT\|}}$	0.339			

Bold values are statistically significant; N=30, p<0.01.

TABLE 2. Spearman's correlation coefficients for $S_{i_{|\Delta W|}}$, $S_{i_{|\Delta LT|}}$, $S_{i_{|\Delta DT|}}$, $S_{i_{|\Delta AT|}}$ and γ at the end of the rehabilitation treatment [6].

	$S_{i_{\|\Delta W\|}}$	$S_{i_{\|\Delta DT\|}}$	$S_{i_{\|\Delta AT\|}}$	$S_{i_{\|\Delta LT\|}}$
γ	0.196	0.121	-0.058	0.081
$S_{i_{\|\Delta LT\|}}$	0.026	**0.464**	**0.777**	
$S_{i_{\|\Delta AT\|}}$	0.060	**0.672**		
$S_{i_{\|\Delta DT\|}}$	0.043			

Bold values are statistically significant; N=30, p<0.01.

significance of the difference between the median values of γ obtained at the end of the rehabilitation process and at its onset; p<0.001 (p=0.0000001). The sign test was used as the distribution of the difference was neither normal nor symmetrical [6]. Fig. 8 illustrates changes in the values of γ observed for a sample patient rehabilitated after total hip arthroplasty.

Tables 1 and 2 present the values of correlations existing between $S_{i_{|\Delta W|}}$, $S_{i_{|\Delta LT|}}$, $S_{i_{|\Delta DT|}}$, $S_{i_{|\Delta AT|}}$ and γ, obtained at the beginning and at the end of the rehabilitation treatment, respectively [6]. One can clearly see that there are no significant correlations between γ and the symmetry measures computed in case of static posturography. This observation supports the statement that γ quantifies other aspects of postural symmetry.

V. CONCLUSIONS

In the article a new concept of postural symmetry assessment, based on the follow-up posturography, has been introduced. The whole idea of the presented approach boils down to the evaluation of the degree of similarity of the counter-clockwise follow-up CoP trajectory and the mirror image against the y-axis of the clockwise follow-up CoP trajectory. This evaluation is carried out using covariance coefficients and the so-called half-plane averaging of the follow-up CoP trajectories. The obtained synthetic measure γ quantifies likeness of the corresponding temporary and average displacements of the CoP, registered in response to the clockwise and counter-clockwise visual stimuli. It's worth to remind that the applied stimuli are mutually symmetrical from the perspective of the left and right lower limbs (symmetry against the y-axis). This way the examined subject is stimulated to load both of his/her limbs in a mutually symmetrical manner.

Statistical analysis confirmed significance of changes in the values of γ obtained in the group of patients rehabilitated after total hip arthroplasty. There were, however, no significant correlations between γ and $S_{i_{|\Delta W|}}$, $S_{i_{|\Delta LT|}}$, $S_{i_{|\Delta DT|}}$, $S_{i_{|\Delta AT|}}$ both at the beginning and at the end of the rehabilitation program. This observation supports the statement that γ quantifies other aspects of postural symmetry, namely the dynamic ones, corroborating also the diagnostic value of the presented method.

One of the advantages of the herein discussed postural symmetry assessment method is the ability to evaluate one's posture using single-plate posturographic platform. No need for the use of a double-plate posturographic platform or two single-plate ones allows for reduction of expenditures for diagnostic equipment.

The main goal of further research will be evaluation of the usability of the presented concepts in health assessment of patients suffering from other conditions and diseases, e.g. Parkinson's disease.

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