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Posturographic methods for body posture symmetry assessment

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Abstract. The article presents a number of posturographic methods enabling objective postural symmetry assessment in patients undergoing rehabilitation after total hip replacement surgery. The key goal of such rehabilitation is fast restoration of a proper body weight distribution. The postural symmetry measures proposed in the article enable generalized quantification of the CoP (Center of Pressure) trajectories measured during standard static posturography diagnostics and the so-called follow-up posturography examination. The follow-up posturography is a relatively new but promising method of physical rehabilitation. All of the herein discussed posturographic measures have been designed specifically to quantify postural symmetry either in a standing and relaxed upright position, in the absence of any deterministic external stimulation (static posturography) or in the presence of a visual biofeedback stimulation enforcing the coordinated slow swaying movements of the body (the follow-up posturography). The experimental results presented in this paper constitute the outcome of the long-term cooperation between the Institute of Electronics of the Silesian University of Technology and the Silesian Rheumatology and Rehabilitation Hospital. The usefulness of the proposed postural symmetry measures has been verified in a series of clinical trials carried out in a selected group of patients undergoing rehabilitation after total hip replacement surgery.

Key words: posturography, follow-up posturography, postural symmetry assessment, biomedical signal processing.

1. Introduction

Posturography, also known as stabilography, is a non-invasive diagnostic method used for the assessment of the human ability to maintain balance, i.e. keeping the body's center of gravity within its base of support [1]. Maintenance of balance is dependent on information flowing to the brain from the following sensory inputs: eyes (vision), muscles and joints (touch sensation via prioprioceptive and cutaneous feedback), and vestibular apparatus (located in the inner ear and responsible for sensing of spatial orientation) [2]. The brain in response to all of the data, it receives, generates targeted posture stabilizing impulses which stimulate selected muscles of the body [3, 4].

The trajectory of movement of the body's center of gravity, CoG (Center of Gravity), can be a valuable source of information regarding the performance of the human balance system. As the direct tracking of CoG is relatively difficult in realization, the same goal can be achieved indirectly via tracking the net downward force, CoP (Center of Pressure), exerted by a person standing on a specialized measurement device called a posturographic platform [1, 5]. The CoP trajectory is a good approximation of the CoG's horizontal plane movement providing crucial information on the performance of the human balance system. It is commonly referred to as the posturographic or stabilographic trajectory.

As an outcome of the long-term collaboration between the Silesian University of Technology and the Silesian Rheumatology and Rehabilitation Hospital, a number of posturographic measures for body posture symmetry assessment have been proposed, enabling quantitative and objective health evaluation in patients undergoing rehabilitation following total hip replacement surgery. Analyzed posturographic data were acquired in a series of clinical examinations carried out using a double-plate posturographic platform designed and built at the Institute of Electronics of the Silesian University of Technology [6, 7]. The usefulness of the proposed postural symmetry measures has been verified in a selected group of patients rehabilitated after total hip replacement surgery.

The most intuitive and simplest of the utilized postural symmetry quantities is the average loading of the lower limbs measured during a standard static posturography examination. This kind of postural symmetry assessment constitutes an improved version of the so-called test of two scales which in essence boils down to the measurement of the body weight portions transferred through each of the lower limbs [8]. The question may, however, be asked if it is a truly objective measure of symmetry as the averaging of the limb loading involved undoubtedly masks the dynamics of the CoP movement [9]. This question has triggered the authors' quest for other ways of postural symmetry assessment. The findings of the conducted research will be presented in the following sections.

2. Double-plate posturographic platform – design, measurement principles and basic measures quantifying posturographic trajectories

Accurate postural symmetry assessment using posturography should generally involve simulatenous recording of the CoP

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trajectories for the left and right leg. At first the use of two single-plate posturographic platforms positioned next to each other may seem to meet the requirement (left and right foot standing on separate platforms), however, this kind of approach is ineffective as in such a scenario synchronous measurement of both trajectories is not always possible. Additionally, the effect of the body weight transferring from one leg to the other is not taken into account. These are the main reasons why a double-plate platform was built (one plate per foot) where each of its plates is supported by a separate group of three strain gauge transducers [7]. Figure 1 shows where these transducers are located in respect to the left and right plate of the platform (P1–P6). The figure also helps to illustrate the way in which the coordinates of CoPs corresponding to the left (CoP$_L$), right (CoP$_R$) and central trajectories (CoP$_C$) are computed.

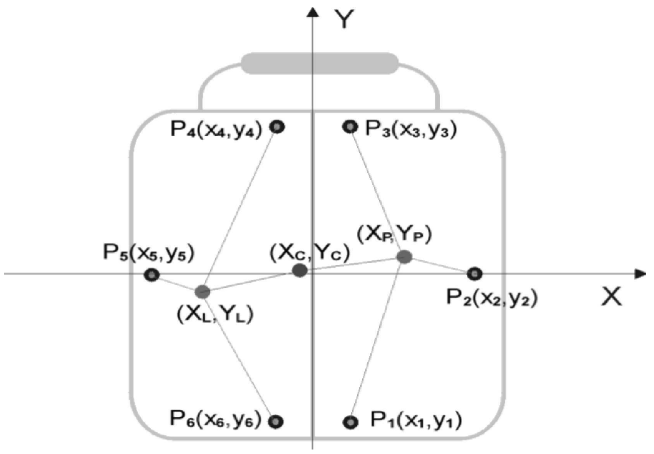

Fig. 1. Double-plate posturographic platform – location of the points of support and illustration of the way in which the coordinates of CoP$_L$, CoP$_R$ and CoP$_C$ are computed

Knowing the Cartesian coordinates of the mounting points of the strain gauge transducers together with the values of forces acting on them, it becomes possible to calculate the coordinates of CoP$_L$(x_L, y_L), CoP$_R$(x_R, y_R) and CoP$_C$(x_C, y_C), which represent the localizations of the net contact forces acting on the platform by the left foot, right foot and both feet, respectively. These coordinates can be obtained using the formulas below (1), (2):

$$X_L^n = \frac{\sum_{j=4}^{6} P_j x_j}{\sum_{j=4}^{6} P_j}, \qquad X_R^n = \frac{\sum_{j=1}^{3} P_j x_j}{\sum_{j=1}^{3} P_j},$$
$$Y_L^n = \frac{\sum_{j=4}^{6} P_j y_j}{\sum_{j=4}^{6} P_j}, \qquad Y_R^n = \frac{\sum_{j=1}^{3} P_j y_j}{\sum_{j=1}^{3} P_j}, \tag{1}$$

$$X_L = X_L^n \frac{\sum_{j=4}^{6} P_j}{\sum_{j=1}^{6} P_j} = \frac{\sum_{j=4}^{6} P_j x_j}{\sum_{j=1}^{6} P_j},$$
$$X_R = X_R^n \frac{\sum_{j=1}^{3} P_j}{\sum_{j=1}^{6} P_j} = \frac{\sum_{j=1}^{3} P_j x_j}{\sum_{j=1}^{6} P_j},$$
$$X_C = X_L + X_R = \frac{\sum_{j=1}^{6} P_j x_j}{\sum_{j=1}^{6} P_j},$$
$$Y_L = Y_L^n \frac{\sum_{j=4}^{6} P_j}{\sum_{j=1}^{6} P_j} = \frac{\sum_{j=4}^{6} P_j y_j}{\sum_{j=1}^{6} P_j}, \tag{2}$$
$$Y_R = Y_R^n \frac{\sum_{j=1}^{3} P_j}{\sum_{j=1}^{6} P_j} = \frac{\sum_{j=1}^{3} P_j y_j}{\sum_{j=1}^{6} P_j},$$
$$Y_C = Y_L + Y_R = \frac{\sum_{j=1}^{6} P_j y_j}{\sum_{j=1}^{6} P_j},$$

where P_j – force exerted on the j-th strain gauge transducer, x_j, y_j – Cartesian coordinates of the j-th strain gauge transducer (the point of support) relative to the center of posturographic platform.

In (1) the effect of transferring body weight from one leg to the other was not considered whereas in (2) it was included, hence the coordinates were properly scaled. Figure 2 illustrates the examples of left and right leg trajectories (along with the corresponding trajectory of the whole body) acquired during a typical static posturography examination. The effect of body weight transfer from one leg to the other was not included, therefore the trajectories appear to be very "narrow". In Fig. 3 the same data was presented, however, this time the effect of body weight transfer was included, resulting in proper scaling of the trajectories. Summation of the left and right leg trajectory produces the trajectory of the whole body, which is also referred to as central trajectory. To make the data presented in Figs. 2 and 3 more readable, the scale of trajectories was set as much larger than the scale of the distances between them.

Measurement of the downward forces exerted on the platform by an examined patient is realized with the MEGATRON KM500 strain gauge transducers, characterized by a relatively good sensitivity of 0.004 mV/V/N and linearity not worse than 0.05% of the full measurement range. Figure 4 illustrates the signal processing path for each of the six strain gauge transducers mounted in the platform.

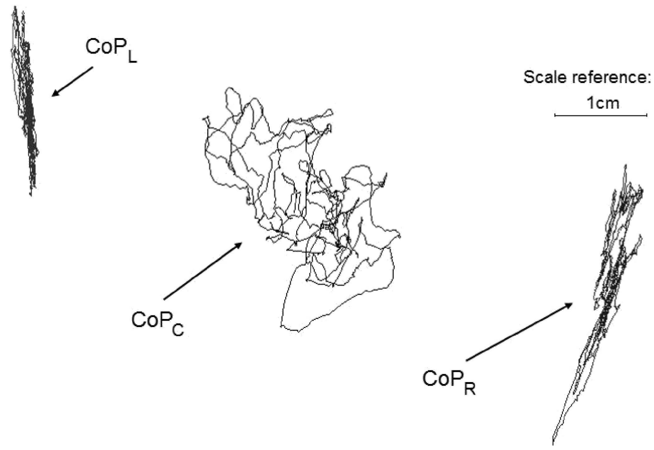

Fig. 2. Sample trajectories of CoP_L, CoP_R and CoP_C obtained during static posturography examination – the effect of the body weight transfer between the legs was ignored

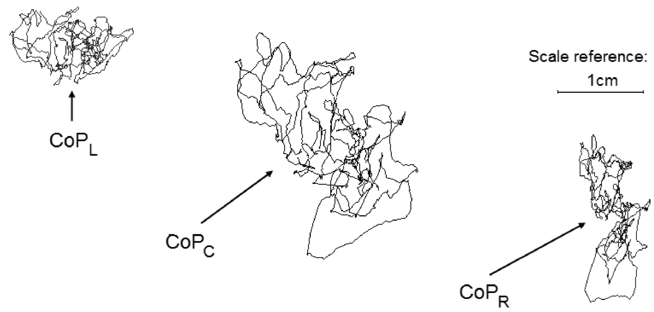

Fig. 3. Sample (scaled) trajectories of CoP_L, CoP_R and CoP_C obtained during static posturography examination – the effect of the body weight transfer between the legs was included

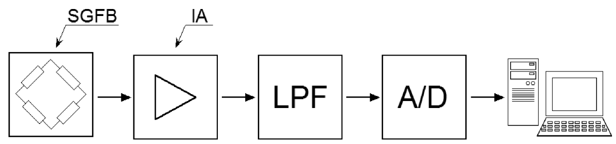

Fig. 4. Block diagram of the signal processing path for each of the six strain gauge transducers mounted in the posturographic platform, where: SGFB – Full Bridge Strain Gauge, IA – Instrumentation Amplifier, LPF – Low-Pass Filter, A/D – Analog to Digital Converter

The voltage signal measured on terminals of the full bridge strain gauge circuit (SGFB) is amplified by the instrumentation amplifier AD620 (IA), whose value of gain is adjustable by a multi-turn precision potentiometer. Given the sensitivity of the transducer, the input voltage range of the 12-bit A/D converter (5 V) and the typical weight of a patient, the amplifier gain was set to about 200 V/V. With a sampling frequency of 50 Hz, an anti-aliasing filter (low-pass 4th-order Butterworth) with a cutoff frequency of 20 Hz was used (LPF).

From Eqs. (1) and (2) it is clear that the measurement resolutions of CoP_L, CoP_R and CoP_C are dependent on the body weight of the patient under examination. Assuming the worst case scenario this dependency for CoP_C can be described by the formulas (3) [7, 10]:

$$\Delta x = \frac{1}{1+\dfrac{M}{d}} \cdot x, \qquad \Delta y = \frac{1}{1+\dfrac{M}{d}} \cdot y, \tag{3}$$

where M – patient body mass, $d = 0.01565$ kg – the smallest measurable value of the downward force acting on the posturographic platform [7, 10]; x, y – the largest distance between the geometrical center of the posturographic platform and the mounting points of the strain gauge transducers for the x coordinate (143 mm for CoP_C and 80.7 mm for both CoP_R and CoP_L) and y coordinate (168.5 mm for CoP_C, CoP_R and CoP_L), respectively.

Figure 5 shows the measurement resolution for the y coordinate of CoP_C as a function of an examined patient's body mass. From inspection it is clear that for patients weighting more than 50 kg the resolution is not worse than 0.05 mm. Even though the function is the same for CoP_R, CoP_L and CoP_C, the weight acting on each of the platform plates is approximately equal to half the whole body weight, hence for a patient weighting 70 kg the resolution in the y-direction is about 0.08 mm per plate. The CoP_C resolution in the x-direction (for adults weighting more than 50 kg) is not worse than 0.04 mm, whereas resolutions of CoP_L and CoP_R are about 0.05 mm [7].

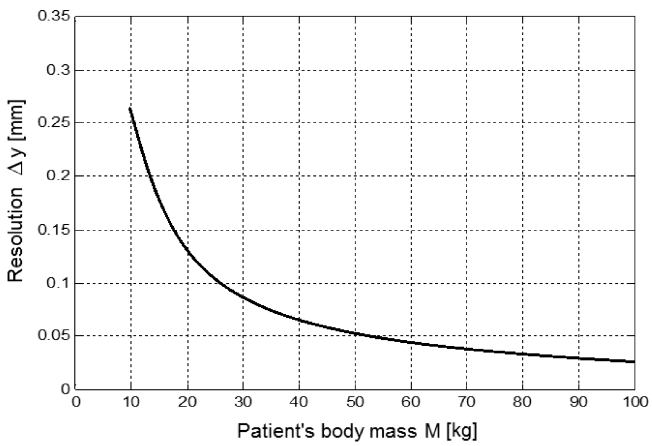

Fig. 5. Measurement resolution for y coordinate of CoP_C as a function of an examined patient's body mass

A number of measures quantifying various features of posturographic trajectories can be derived [6, 7, 11, 12]. Only those which are interesting from the perspective of postural symmetry assessment (their definitions refer to the trajectory of the whole body – CoP_C) are presented below:

- LT – length of trajectory:

$$\mathrm{LT}_C = \sum_{i=2}^{N} l(i), \tag{4}$$

where

$$l(i) = \sqrt{\left[x_C(i) - x_C(i-1)\right]^2 + \left[y_C(i) - y_C(i-1)\right]^2}, \tag{5}$$

- AT – area under the unrolled trajectory:

$$\mathrm{AT}_C = \sum_{i=2}^{N} p(i), \tag{6}$$

where

$$p(i) = \sqrt{a^* \cdot [a^* - r(i-1)] \cdot [a^* - r(i)] \cdot [a^* - l(i)]}, \tag{7}$$

where

$$a^* = ob(i),$$

$p(i)$ is the surface area of a triangle comprised of two successive points of a given trajectory ($T_c(i-1)$, $T_c(i)$) and the point T_{c0} representing the center of that trajectory (Fig. 6); $l(i)$ is given by formula (5) whereas values of $r(i)$, $r(i-1)$ and $ob(i)$ are calculated using the following equations:

$$r(i) = \sqrt{[x_C(i) - x_{C0}]^2 + [y_C(i) - y_{C0}]^2}, \tag{8}$$

$$r(i-1) = \sqrt{[x_C(i-1) - x_{C0}]^2 + [y_C(i-1) - y_{C0}]^2}, \tag{9}$$

$$ob(i) = \frac{l(i) + r(i) + r(i-1)}{2}, \tag{10}$$

- DT – average CoP deviation from the center of trajectory:

$$\mathrm{DT}_C = \frac{\sum_{i=1}^{N} r(i)}{N}, \tag{11}$$

where N – number of points comprising the trajectory, $r(i)$ – distance of the i-th point of the trajectory from its center T_{c0} (Fig. 6), given by formula (8).

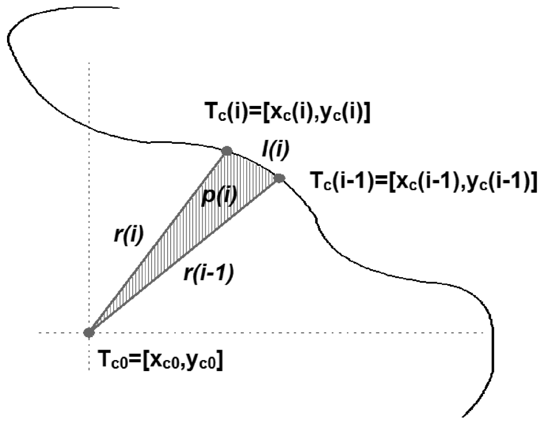

Fig. 6. Calculation of the surface area under the posturographic trajectory

Standard posturographic examination, also known as static stabilography, boils down to recording CoP trajectories of patients standing on the measurement platform in a relaxed upright position [7, 13]. During such an examination there are no external deterministic impressions that might stimulate the human balance system. This kind of examination is useful and well established in the medical community; however, its main disadvantage is the aforementioned lack of imposed determinism in the way the patient behaves while standing on the platform. Clinical experiments conducted by the authors of this paper indicate that much more valuable diagnostic data can be obtained during the examination with a deterministic external stimulation [6]. As a result of the long-term cooperation between the Institute of Electronics of the Silesian University of Technology and the Silesian Rheumatology and Rehabilitation Hospital, an original method was developed for postural symmetry training for patients rehabilitating after total hip replacement surgery. The method utilizes the so-called follow-up posturography with a visual biofeedback stimulation adapted to the current health state of the patient [10, 14–16]. During the training the patient standing on the posturographic platform is supposed to balance their body in such a way that their CoP trajectory, which is visualized on the computer screen, should coincide with the trajectory of the deterministic visual stimulation. The point of the observed visual stimulus moves with a constant angular velocity drawing a circle around the center of the Cartesian coordinate system, first in the clockwise and next in the counterclockwise direction. The period of the movement around the circle in each direction is 60 seconds. Figure 7 shows the trajectory of the counterclockwise visual stimulus together with a corresponding sample follow-up trajectory. Quantification of such follow-up trajectories using specifically chosen measures enables evaluation of the patient's health status in the presence of deterministic external impressions. This allows for a more reliable assessment of the physical rehabilitation process following total hip replacement surgery.

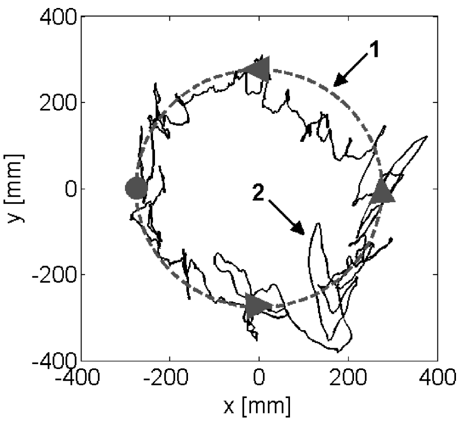

Fig. 7. Trajectory of the visual stimulus (1) with a corresponding CoP_C follow-up trajectory of an examined patient (2) – both visualized on a computer screen in front of the patient standing on the posturographic platform

3. Posturographic methods for body posture symmetry assessment

Absolute posturographic measures presented in the previous section constitute the baseline for the herein proposed relative measures of postural symmetry. Effective evaluation of changes in the state of health of patients undergoing rehabilitation after total hip replacement surgery requires a new postural symmetry assessment approach, one which is insensitive to certain masking and distorting influences introduced by the rehabilitation process itself. Analysis of posturographic data acquired in a series of clinical trials conducted in the Silesian Rehabilitation and Rheumatology Hospital indicates the superiority of the relative measures of symmetry, i.e. measures computed individually for the left and right leg trajectories related to the sum or difference of these quantities. This way the differences in features of the left and right leg trajectories quantified by the absolute posturographic measures become emphasized.

3.1. Loading of the lower limbs. In medical circles there are known methods enabling assessment of the lower limb loading symmetry which utilize the so-called test of two scales. This kind of approach, however, is subject to a number of errors, seriously limiting the capabilities of these methods. Precise symmetry assessment can be carried out with the use of a double-plate posturographic platform which allows for simultaneous measurement of the downward forces exerted on the platform separately by left and right foot. Net forces acting on the left or right plate at a given moment in time can be calculated as the sum of forces measured by the three strain gauge transducers supporting the plate (Fig. 1) using the formulas below (12):

$$P_R(i) = \sum_{j=1}^{3} P_j(i), \qquad P_L(i) = \sum_{j=4}^{6} P_j(i), \tag{12}$$

where j – index of the j-th strain gauge transducer, i – time of the measurement, $P_j(i)$ – force measured by j-th strain gauge transducer; $P_R(i)$, $P_L(i)$ – net downward force exterted on the right and left plate of the platform, respectively.

The formulas below in (13) can be used to compute the average loading which acts on the right (W_R) and left (W_L) plate of the platform:

$$W_R = \frac{\sum_{i=1}^{N} P_R(i)}{N}, \qquad W_L = \frac{\sum_{i=1}^{N} P_L(i)}{N}. \tag{13}$$

The average limb loading quantity is a useful indicator of the state of health of patients undergoing rehabilitation after total hip replacement surgery. Pilot studies carried out in the Silesian Rheumatology and Rehabilitation Hospital, however, have shown there is a need for more specific analysis of the data acquired during a standard static posturography [6, 17]. It turns out that the precision of health assessment using absolute measures may be significantly impacted by considerable changes in patient body weight manifested over the course of the rehabiliation program [6]. These changes can be associated with increased physical activity directly resulting from the hip replacement surgery (it is particularly true for elderly people). In order to clarify the issue, let us consider a simple case assessing two patients with distinctly different body weights. Let's assume that the average loading in case of the first patient is 50 kg for the left and 70 kg for the right leg. In the case of the second patient, the average loading will be 30 kg and 10 kg for the left and right leg, respectively. Of course, the loading of the limb with a hip endoprotsthesis is smaller. The difference between the loads acting on the left and right plate of the platform is 20 kg in either case. The question could be raised as to whether such an absolute method of postural symmetry assessment is appropriate. Analysis of clinical data has provided a negative answer to this question [6]. Clinical trials have shown that the symmetry of loading of the lower limbs should rather be assessed as the ratio of the load extorted by the limb with the endoprosthetic implant to the weight of the whole body (or the ratio of difference of loads extorted by the left and right leg to the whole body weight). This way the relative limb loading symmetry measure (S_n) can be formulated (14):

$$S_n = \frac{W_E}{W_L + W_R}, \tag{14}$$

where W_E – average load extorted on the measurement platform by the limb with an endoprosthetic implant; W_L, W_R – average loads extorted on the measurement platform by the left and right leg, respectively.

S_n equal to 0.5 represents the ideal limb loading symmetry. For S_n greater than 0.5, the limb with an endoprosthetic implant experiences overloading, whereas for S_n smaller than 0.5 it is underloaded. It is worth emphasizing that this type of postural symmetry evaluation is independent of patient body weight changes which normally take place over the course of the rehabilitation program.

3.2. Relative measures quantifying the degree of similarity between left and right leg posturographic trajectories. Studies have shown that the approach presented in the previous section should also be taken in case of other posturographic measures [6]. Absolute quantities such as the surface area under the unrolled trajectory, length of the trajectory or the average CoP deviation from the trajectory center are highly variable for individual patients. Additionally, they are dependent on patient age, previous injuries and general mobility. As it turns out these dependencies can be substantially minimized if resorting to the relative approach, using the following generalized formula (15):

$$S_x = \frac{\Psi_E}{\Psi_L + \Psi_R}, \tag{15}$$

where S_x – relative symmetry measure; Ψ_L, Ψ_R, Ψ_E – absolute posturographic measures(eg. surface area under the unrolled trajectory, length of the trajectory, etc.) corresponding to the left limb (Ψ_L), right limb (Ψ_R) and the limb with endoprosthetic implant (Ψ_E), respectively.

This kind of symmetry evaluation minimizes the dispersion of the values obtained for absolute quantities, emphasizing the differences between the left and right leg trajectories. In the next sections the following three types of relative postural symmetry measures will be evaluated (16):

$$S_{AT} = \frac{AT_E}{AT_L + AT_R}, \qquad S_{LT} = \frac{LT_E}{LT_L + LT_R}, \qquad S_{DT} = \frac{DT_E}{DT_L + DT_R}, \tag{16}$$

where S_{AT} – relative surface area under the unrolled trajectory, S_{LT} – relative length of the trajectory, S_{DT} – relative average CoP deviation from the trajectory center.

All of the constituent absolute measures can be calculated using formulas: (4), (6) and (11).

3.3. Classification of posturographic trajectories using shape symmetry measures. A different method for postural symmetry assessment is attained by quantifying the bilateral and rotational symmetry degree of the CoP_C trajectory recorded during the follow-up posturography test session [18]. The evaluation of postural symmetry with the use of follow-up posturography is particularly valuable as it enables analysis of the dynamics of changes in body weight distribution in the presence of an external deterministic visual stimulation.

Shape symmetry is one of the most fundamental features of the world around us. Our brain automatically assesses and classifies perceived visual impressions, also in terms of their symmetry. Despite the superb performance of these natural mechanisms of observation and analysis, their strictly subjective and qualitative nature is unacceptable from a scientific perspective. Thus, objective and quantitative methods enabling evaluation of different kinds of shape symmetry had to be developed. Two such methods used for quantification of the degree of bilateral and rotational symmetry of the follow-up posturographic trajectories will be presented in this section. Firstly, the concepts of bilateral and rotational symmetry is defined. Next, the interpretation of the corresponding symmetry measures is provided [18–20].

In classical geometry, bilateral symmetry can be defined as the existence of an axis dividing a given shape into two identical parts. To quantify the degree of bilateral symmetry, the Bilateral Central Symmetry Degree – BCSD was formulated [18, 19]:

$$\mathrm{BCSD}(i) = \left.\frac{A\left(M_i' \cap M_i''\right)}{A(M)}\right|_{i=0,1,\ldots,k-1}, \tag{17}$$

where M – examined geometrical figure, M_i' – M rotated counterclockwise about $2\pi i/k$ [rad] around its own centroid, M_i'' – mirror reflection of M_i' with x being the axis of reflection, A – operator returning the value of the surface area of the geometrical figure it is acting on, i – number of the current iteration, k – maximum number of iterations.

Achievable values of the BCSD quantity are in the range of [0, 1], where 1 represents the ideal bilateral symmetry in a given iteration, whereas 0 characterizes total absence of such symmetry.

Another measure of shape symmetry which can be utilized for quantitative classification of posturographic trajectories is the Rotational Central Symmetry Degree – RCSD, associated with the rotational regularity of a given shape. RCSD can be defined as [18, 19]:

$$\mathrm{RCSD}(i) = \left.\frac{A\left(M \cap M_i'\right)}{A(M)}\right|_{i=0,1,\ldots,k-1}. \tag{18}$$

Achievable values of the RCSD quantity are in the range of [0,1], where 1 represents the ideal rotational symmetry in a given iteration, whereas 0 characterizes the total absence of such symmetry.

As an example, shape symmetry measures of an equilateral triangle will be examined. Successive transformations required for computation of BCSD and RCSD values are illustrated in Fig. 8a and 8b, respectively. In Fig. 8a, the continuous sections represent the analyzed triangle rotated counter-clockwise by an angle $2\pi i/k$ around its own centroid. The dashed segments create the mirror reflection of the rotated

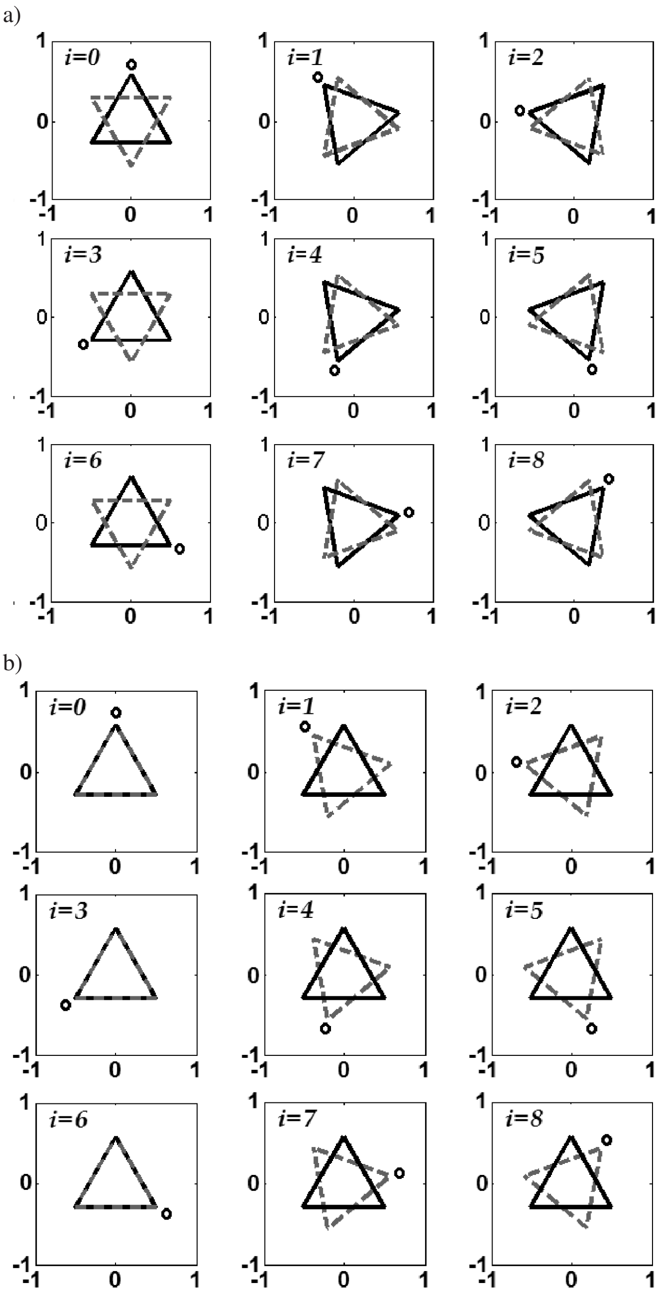

Fig. 8. Geometrical transformations in successive iterations of the algorithm for calculation of a) BCSD(i) and b) RCSD(i), illustrated for an equilateral triangle ($k = 9$)

triangle, with x being the axis of reflection. In Fig. 8b, the continuous lines describe the examined triangle in its original position, whereas the dashed lines constitute the copies of that triangle rotated counterclockwise by an angle $2\pi i/k$ [rad] around its centroid. In addition, to make the presentation clearer, the $^\circ$ symbol was introduced in both figures to mark the current position of one of the vertices of the triangle.

For the sake of simplicity, in the presented case the number of iterations was limited to 9. In practice, however, the value of k should be greater than that, since it directly affects the resolution of BCSD(i) and RCSD(i) functional representations. Figure 9 presents the values of BCSD(i) and RCSD(i) calculated in successive iterations of the algorithms illustrated in Fig. 8a and 8b. To show how the k parameter value affects the resolutions of BCSD(i) and RCSD(i) representations, in Fig. 10 both quantities were calculated for the same equilateral triangle, however, this time with k value being significantly greater ($k = 360$). The k parameter directly determines the angle of rotation expressed by $2\pi i/k$. For instance, if $i = 2$ and $k = 9$ the angle of rotation is equal to $4\pi/9$ [rad]. When $k = 360$ the same angle of rotation can be obtained for $i = 80$. Thus, BCSD(2) for $k = 9$ is equal to BCSD(80) for $k = 360$. Similarly, RCSD(2) for $k = 9$ is equal to RCSD(80) for $k = 360$. It should be noted that too high a value of k may noticeably increase the processing time without bringing any significant improvement in the quality of the results.

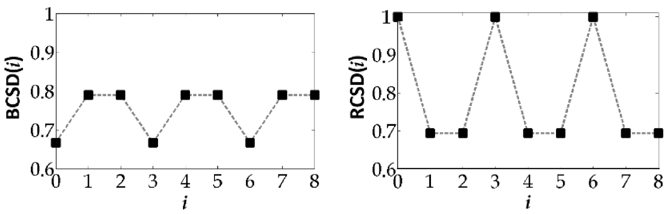

Fig. 9. The values of BCSD(i) and RCSD(i) in successive transformations (iterations) illustrated in Fig. 8a and 8b ($k = 9$)

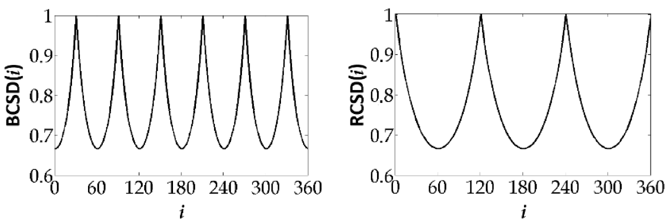

Fig. 10. The values of BCSD(i) and RCSD(i) in successive transformations (iterations) computed for an equilateral triangle, with $k = 360$ (starting orientation of the triangle was the same as in Fig. 8a and 8b)

For practical use of the presented shape symmetry measures the δ_B, δ_R quantities were defined, corresponding to the maximum value of BCSD(i) and RCSD(i), respectively. These quantities can be described using the following two formulas [18, 19]:

$$\delta_B = \max\{\mathrm{BCSD}(i)\}|_{i=0,1,2,\ldots,k-1}\,, \tag{19}$$

$$\delta_R = \max\{\mathrm{RCSD}(i)\}|_{c_1 \le i \le c_2}\,. \tag{20}$$

Since the maxima of RCSD(i) corresponding to the first and last value of the argument i always mask other (more important in terms of rotational symmetry quantification) values of RCSD(i), for computation of δ_R only those values of i are taken into account which belong to $[c1,\ c2]$, where $c1$ represents the position of the first local minimum of RCSD(i), whereas $c2$ refers to the position of the last local minimum of RCSD(i).

To enable assessment of the follow-up trajectories using quantification of the degree of shape symmetry, a method for the extraction of the contour of an examined trajectory and computation of the surface area bounded by it was needed. In the presented solution successive points of an analyzed trajectory are mapped into pixels of an $K \times K$ black and white bitmap. The mapped area is limited by maximum and minimum values of $(x,\ y)$ coordinates found in the set of points comprised of the original trajectory and the same trajectory shifted by the vector $[-x_c,\ -y_c]$, where x_c and y_c are the coordinates of the centroid of the original trajectory. This way the bitmap retains information about the shift of the original trajectory relative to the center of the coordinate system. It is worth noting that in terms of postural symmetry assessment, not only is the shape of the trajectory important, but also its location relative to the center of the coordinate system, which is also the center of the visual stimulus trajectory. To ensure continuity of the envelope of mapped trajectories, especially in case of larger values of K; before the mapping is done, the first point of the analyzed trajectory is copied to the very end of it, just to close the trajectory's contour. Subsequently, the interpolation is performed on the trajectory with an accuracy guaranteeing that the distance between any two consecutive points of the trajectory is smaller than the dimensions of each individual segment of the bitmap, hence continuity of the contour is assured. In the carried out experiments the interpolation was performed using cubic splines curves, independently for x and y components of the analyzed trajectories.

In the process of mapping of the follow-up trajectory into a bitmap, each of the successive points of the trajectory is replaced with a corresponding segment on the bitmap. Each segment within which at least one point of the trajectory is found is assigned with a non-zero integer value which unambiguously identifies the mapped points of the trajectory. All other segments are then assigned with the value of zero. In the next step segments constituting the contour of the trajectory and the segments located in its interior are extracted.

Examples of such trajectory mapping for different values of K are illustrated in Figs. 11 and 12. In the proposed approach for computation of RCSD(i) and BCSD(i), instead of ratios of real surface areas, the ratios of numbers of bitmap segments making up these areas are used. It is clear that the better the resolution of the bitmap, the better the accuracy of the mapping. In the final step of the algorithm the resulting image is subjected to transformations required for calculation of δ_B and δ_R (17)–(20).

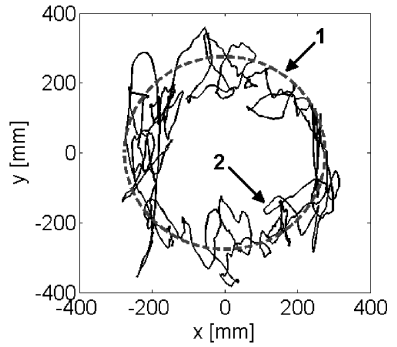

Fig. 11. Trajectory of the visual stimulus (1) with an example of the corresponding CoP_C follow-up trajectory (2)

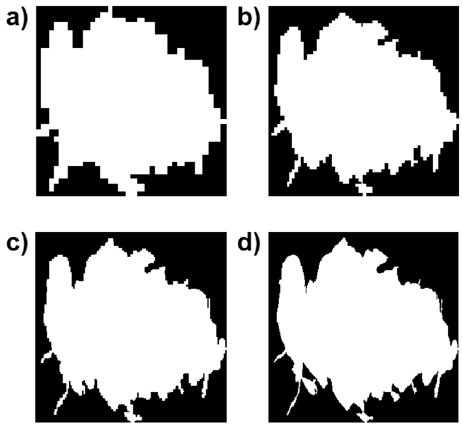

Fig. 12. Bitmaps representing the contour of the CoP_C follow-up trajectory shown in Fig. 11, obtained for different resolutions: a) $K = 32$, b) $K = 64$, c) $K = 128$, d) $K = 256$

4. Results of clinical trials

To verify the applicability of the proposed postural symmetry measures, the process of patient rehabilitation after total hip replacement surgery was thoroughly studied. The study involved a group of 60 patients ($N = 60$) with one hip joint endoprosthesis and without any known health issues which might have interfered with the postural symmetry evaluation process, e.g. severe pain in the operated hip joint or other joints, periarticular ossification within the endoprosthesis, monocular vision and a number of others [6]. The rehabilitation was carried out in the Silesian Rheumatology and Rehabilitation Hospital located in Ustroń, Poland. In the group of 30 patients ($N = 30$) a typical scheme of exercises was supplemented with symmetry training using the follow-up posturography with a visual biofeedback adapted to the current health state of the patient [6, 17]. Before each of such training sessions, static posturography (with open eyes) was performed, allowing for computation of the proposed relative postural symmetry measures (14), (15), i.e. S_n, S_{LT}, S_{DT}, S_{AT}. After the static posturography the follow-up examination with a circular visual stimulation was conducted (shape of the trajectory to follow was a circle). Measured trajectories were then analyzed in terms of their contour symmetry. The follow-up posturography was carried out twice a day – before and after the physical rehabilitation exercises. In the evaluated group of patients statistically significant changes have been observed in the values of all of the proposed postural symmetry measures.

Statistical analysis of the data acquired during the static posturography (Student's t-test) showed that the rehabilitation program brought very significant improvement in the limb loading symmetry ($p = 0.000005$) (14). As far as AT and DT quantities are concerned their mean values were lower at the end of the rehabilitation program than at its beginning (Fig. 13). In case of mean LT value a slight increase was observed (Fig. 13). Decrease in values of AT, DT and LT is usually an indication of improvement in patient's ability to maintain balance.

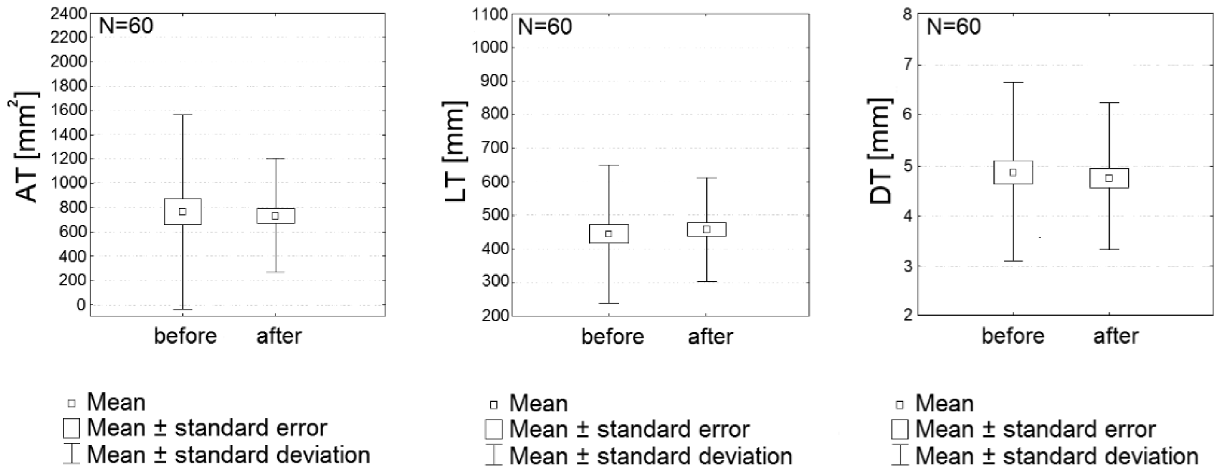

Fig. 13. Mean values of the absolute posturographic measures calculated for CoP_C trajectories obtained during static posturography examinations before and after the rehabilitation following total hip replacement surgery, where: AT – surface area under the unrolled trajectory, LT – length of the trajectory, DT – average deviation of CoP_C from the trajectory's center

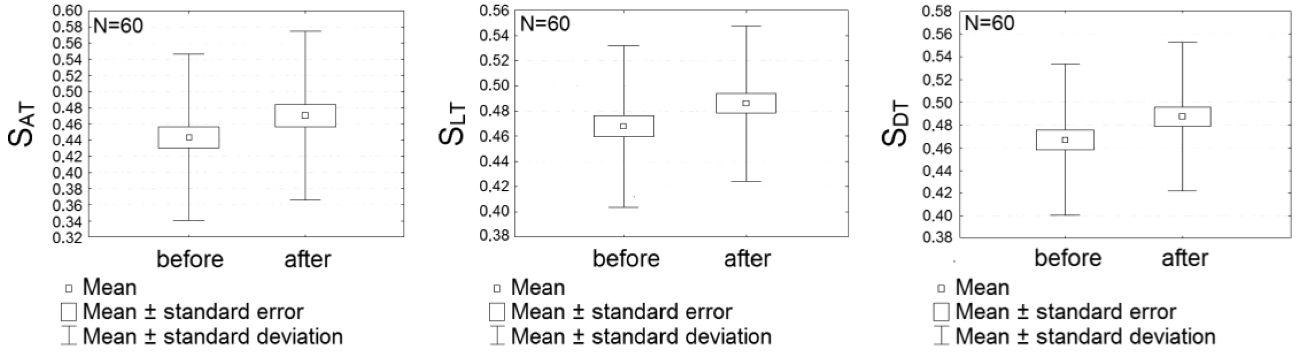

Fig. 14. Mean values of the relative postural symmetry measures obtained during posturographic examinations conducted before and after the rehabilitation following total hip replacement surgery, where: S_{AT} – relative surface area under the unrolled trajectory, S_{LT} – relative length of the trajectory, S_{DT} – relative average deviation of CoP from the trajectory's center

The measures were also computed for trajectories of the left and right leg, individually. Average values for all of the measures obtained for the limb with an endoprosthetic implant were greater after the rehabilitation than before it. For the limb without the implant, the opposite was observed. This indicates restoration of the dynamic functions of the limb with endoprosthesis as the result of the applied rehabilitation program.

Due to the patient-specific variability of the absolute posturographic measures, i.e. their strong dependency on age (the values of all of the discussed absolute quantities significantly increase with age), evaluation of the current health status of patients based on these measures is not particularly effective. In this respect, much more valuable are the relative measures formulated in (15) and (16). Over the course of the rehabilitation program their values change significantly, tending to a value of 0.5. Graphs juxtaposing statistics of these measures obtained before and after the rehabilitation are shown in Fig. 14.

Statistical analysis (Student's t-test for dependent variables, $N = 60$) showed highly significant changes in the mean values of the proposed relative postural symmetry measures (Fig. 14). The values after the rehabilitation were closer to the value of 0.5 which represents the ideal symmetry. In case of the relative area under the unrolled trajectory (S_{AT}), its mean value of 0.444 from before the rehabilitation rose to 0.470 after it. The difference of mean values was statistically significant (Student's t-test for dependent variables, $p = 0.0437$). Similarly, statistically significant differences in the mean values were observed for other quantities. In case of the relative length quantity (S_{LT}) its mean value of 0.486 obtained at the end of the rehabilitation program was significantly greater than the value of 0.468 assessed before the program was started ($p = 0.0201$). There was also a statistically significant difference between the mean values of the relative average deviation of CoP from the trajectory's center (S_{DT}) obtained before (0.467) and after (0.487) the rehabilitation ($p = 0.0456$).

Postural symmetry can also be evaluated using δ_B, δ_R measures, quantifying the degree of contour symmetry of the follow-up trajectory. Figure 15 shows the values of δ_B and δ_R calculated for a typical patient in successive days of the rehabilitation program after total hip replacement surgery. The upward trends observable in both graphs reflect the gradual increase in bilateral and rotational symmetry of the follow-up trajectories.

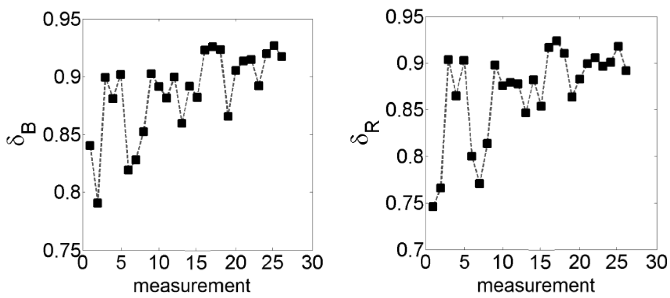

Fig. 15. Measures δ_B, δ_R computed for a typical patient in successive days of the physical rehabilitation program following total hip replacement surgery. The values were obtained for clockwise visual stimulation, $K = 64$ and $k = 64$

Figure 16 shows a two-dimensional equivalent of the two graphs presented in Fig. 15. The colors of points depict various stages of the rehabilitation process. The warmer the color the closer to the end of it. It should be noted that due to the intrinsic instability of the human balance system, even for healthy people, it is virtually impossible to obtain values of δ_B, δ_R equal to 1. The case of perfect symmetry may be treated just as the point of reference in the assessment of the degree of regularity of the follow-up trajectories, however, it should never be the goal of the rehabiliation per se.

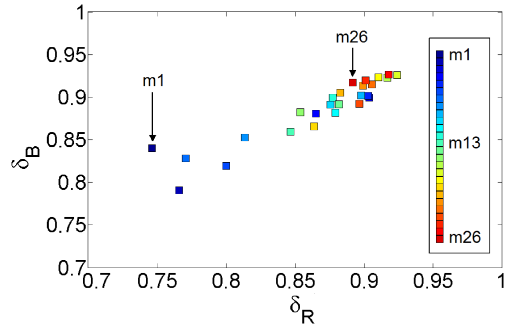

Fig. 16. Two dimensional representation of the data presented in Fig. 15, where m1–m26 denote successive measurement points

Table 1
Mutual correlations of the proposed postural symmetry measures before the rehabilitation

	Pearson's correlation coefficient for $N = 30$; Red marked values are statistically significant, $p < 0.05$; CW – clockwise visual stimulation, CCW – counterclockwise visual stimulation						
	S_{AT}	S_{LT}	S_{DT}	$\delta_{B(CW)}$	$\delta_{R(CW)}$	$\delta_{B(CCW)}$	$\delta_{R(CCW)}$
S_n	0.262917	**0.383597**	0.278646	−0.146997	−0.099556	−0.223829	−0.109675
S_{AT}		**0.879219**	**0.857575**	−0.10418	−0.139476	−0.113347	−0.072667
S_{LT}			**0.711495**	0.04405	−0.11461	−0.048603	−0.001208
S_{DT}				−0.052829	−0.14537	−0.098041	−0.083805
$\delta_{B(CW)}$					**0.782813**	**0.458195**	**0.474747**
$\delta_{R(CW)}$						0.258555	**0.36253**
$\delta_{B(CCW)}$							**0.800067**

Table 2
Mutual correlations of the proposed postural symmetry measures after the rehabilitation

	Pearson's correlation coefficient for $N = 30$; Red marked values are statistically significant, $p < 0.05$; CW – clockwise visual stimulation, CCW – counterclockwise visual stimulation						
	S_{AT}	S_{LT}	S_{DT}	$\delta_{B(CW)}$	$\delta_{R(CW)}$	$\delta_{B(CCW)}$	$\delta_{R(CCW)}$
S_n	**0.396568**	**0.336595**	**0.370371**	−0.006926	−0.051035	0.050012	0.002819
S_{AT}		**0.93665**	**0.881628**	0.045325	0.031931	0.176311	0.206365
S_{LT}			**0.813795**	0.008528	0.01322	0.077305	0.11066
S_{DT}				0.062588	0.056537	0.180243	0.194667
$\delta_{B(CW)}$					**0.966412**	**0.74432**	**0.785903**
$\delta_{R(CW)}$						**0.726843**	**0.772352**
$\delta_{B(CCW)}$							**0.965647**

Having proposed a number of quantities for postural symmetry assessment, the question arises whether they are mutually correlated. While the relative limb loading measure is quite intuitive and does not raise any doubts, the applicability of other relative measures discussed in this article might be debatable. The use of shape symmetry quantifying measures might also bring some questions. Thus, it is worth calculating mutual correlations of all of these postural symmetry measures. Table 1 and Table 2 contain values of Pearson's linear correlations computed for pairs of respective coefficients before (Table 1) and after (Table 2) the rehabilitation following total hip replacement surgery.

Contents of Table 1 and Table 2 prove very strong mutual correlations within the groups of relative and shape symmetry quantifying measures, and rather lack of correlation between the groups themselves. Larger correlational coupling was noticed after the rehabilitation program. The highest values of Pearson's linear correlation were observed in the group of relative measures. The mutual correlation of S_{AT} and S_{LT} was equal to 0.933665. S_{AT} and S_{DT} were correlated at the level of 0.881628 whereas mutual correlation of S_{LT} and S_{DT} was equal to 0.813795. Indeed the values in Table 1 and Table 2 prove a very strong mutual statistical coupling between all of the newly proposed relative measures (15), however, these measures are not so strongly correlated with the quantity reflecting the relative loading of the limb (S_n). After the rehabilitation the values of respective correlations were in the range of 0.336595–0.396568. Before the rehabilitation statistically significant correlational coupling was observed only between S_{LT} and S_n (0.383597). Significant mutual correlations were detected within the group of bilateral and rotational symmetry measures obtained for the follow-up posturographic trajectories, however, there were no significant correlations between them and other postural symmetry measures.

Undoubtedly, the values of all of the proposed measures of symmetry significantly change in the process of physical rehabilitation following total hip replacement surgery, enabling objective and quantitative postural symmetry assessment. The results of conducted statistical analysis indicate that different groups of symmetry measures evaluate different aspects of symmetry, i.e. the symmetry of loading of the limbs, the symmetry of posture in a relaxed standing upright position and the symmetry of posture in the presence of a deterministic visual stimulation. Lack of unequivocal correlational coupling between these groups may, indeed, indicate that measures in each group quantify different aspects of postural symmetry providing different diagnostic information. Confirmation of this reasoning, however, requires a much larger number of experiments which should be discussed in a broader group of orthopedic and rehabilitation specialists.

5. Conclusions

The symmetry measures proposed in this article provide means for a simple and effective postural symmetry assessment, ready for use in clinical practice. Experimental research conducted in the Silesian Rheumatology and Rehabilitation Hospital has proven their usefulness in evaluation of the health state of patients rehabilitated after total hip replacement surgery. Objective assessment of postural symmetry is in this case extremely important, as in a relatively short period of time after the operation, patients should regain correct body posture. This, however, requires symetrization of loading of the lower limbs which involves restoration of the dynamic capabilities of the limb with an endoprosthetic implant. It is worth noting that constant overloading of the limb with endoprosthesis may lead to premature wear of the implant. On the other hand, notorious overloading of the limb with natural joints may be detrimental to its healthy tissues.

Results presented in this article constitute the outcome of many years of collaborative research of the authors. The main goal of the conducted studies was finding more effective postural symmetry measures enabling objective health evaluation in patients rehabilitated after total hip replacement surgery. As a result, a number of clinically verified measures for postural symmetry assessment have been proposed. Further research activities will be related to the clinical evaluation of all of these measures strictly in terms of their applicability to the follow-up posturography used in assistance to the physical rehabilitation following total hip replacement surgery.

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