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The Standard Deviation of Differential Index as an innovation diagnostic tool based on kinematic parameters for objective assessment of a upper limb motion pathology

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Purpose: Indexing methods are very popular in terms of determining the degree of disability associated with motor dysfunctions. Currently, indexing methods dedicated to the upper limbs are not very popular, probably due to difficulties in their interpretation. This work presents the calculation algorithm of new *SDDI* index and the attempt is made to determine the level of physical dysfunction along with description of its kind, based on the interpretation of the calculation results of *SDDI* and *PULMI* indices. *Methods*: 23 healthy people (10 women and 13 men), which constituted a reference group, and a group of 3 people with mobility impairments participated in the tests. In order to examine possibilities of the utilization of the *SDDI* index the participants had to repetitively perform two selected rehabilitation movements of upper extremities. During the tests the kinematic value was registered using inertial motion analysis system MVN BIOMECH. *Results*: The results of the test were collected in waveforms of 9 anatomical angles in 4 joints of upper extremities. Then, *SDDI* and PULMI indices were calculated for each person with mobility impairments. Next, the analysis was performed to check which abnormalities in upper extremity motion can influence the value of both indexes and interpretation of those indexes was shown. *Conclusion*: Joint analysis of the both indices provides information on whether the patient has correctly performed the set sequence of movement and enables the determination of possible irregularities in the performance of movement given.

Key words: *upper extremities, upper limb motion pathology, indexes, pathology, SDDI, PULMI*

1. Introduction

Methods of evaluation of movement dysfunction based on motion indices are often used because of their advantages. It should be noted that they are the most objective way of determining the level of disorders of the human musculoskeletal system [19], [20]. Based on the values measured they enable the determination of the level of disability, often with the ability to identify its type.

Classification and degree of disability can be determined using various scales like GMFCS (Gross Motor Function Classification Scale) [12], [17] which is based on observations whether patient can perform certain established moves, or on BMFM scale (Bimanual Fine Motor Function) [4], which verifies patient's manual dexterity. The level of patients' motor dysfunctions described this way requires the involvement of an experienced therapist who conducts certain tests based on their knowledge and experience [1], [5], [18]. Therefore, the evaluation done by different therapists may result in different scores in the adopted scale, which is the main disadvantage of indexing methods based on classification [13]. Such methods of determining the level of mechanical disturbance of the human body are not objective tools.

Slightly better way to assess the level of disorders of the human movement are indexing methods, in which the rates are calculated based on the objective

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measurements of motion, and then compared with the defined pattern based on measurements of healthy people. These methods have found wide approval due to their objectivity and quickness of calculations of the indices, (result of which can be obtained during the time of examination). These methods were primarily used in the researches of gait, which is a highly repeatable, ontogenetic operation, and thus it is easy to define the correct motor standard. An example of this type of research methods include Schute [15], Schwartz [16] and Rozumalski [14]. These authors set out the *GDI* and *GGI* indices to assess the pathology gait of children with cerebral palsy. There is also the possibility of using indexing methods in assessing imbalances, which was also shown in Michnik's researches [11].

In the case of the upper limbs there is much greater individuality in the way of performing movements and also bigger is the complexity of the movements and their differentiation, as confirmed by Jaspers [8] and Butler [2]. There are also increased deviations of standards in the case of setting out benchmarks for, among others, the time value of anatomical angles in the joints during daily activities [6]. These differences may occur due to the fact that the movements of the upper limbs during everyday tasks are much less likely to repeat than the movements of the lower limbs, for example during walking. The resulting difficulties in the interpretation of often ambiguous test results make the indexing methods for the upper limbs movement being used much less frequently.

However, there are computational methods that have been used to calculate the level of movement disorders of the upper limb such as APS used in Jaspers studies [9] or *PULMI* index (The Paediatric Upper Limb Motion Index) [2]. The latter is defined based on recorded time changes of the values of the anatomical angles in the joints of the upper limb while performing movements and the obtained value expresses clearly the degree of difference from the established norm.

Analysing the algorithm of *PULMI* index calculations, which is based on determining the value of the *RMS* (Root Mean Square) between the course of the test [2] and a reference value, enables the determination of the characteristic fragments of courses on which the index value changes. For example, the shift in the anatomical angles charts along the axis of values may occur if there is a different starting position while performing the movement or it may depend on the calibration of the system made for analysing the motion (poorly calibrated system may, for example, result in appearing a zero error which also affects the value of *RMS*). Using the *PULMI* index one can analyse the distance of the angular waveforms from one another, which reflects the irregularity in the performance of the moves.

It is, therefore, necessary to extend the evaluation of the level of dysfunction of movement in the area of the upper limbs over the additional index, which, in contrast to the *PULMI* index would react only to the change of the waveforms. This index alone or with *PULMI* would allow unambiguous determination of the level of physical dysfunction at the same time attempting to indicate its type whether it is the result of the "shift" in relation to a pattern or is it a different way of making a move.

The chief aim of this study is to develop a new index – *SDDI* (The Standard Deviation of Differential Index) which will allow complementing the assessment of the level of dysfunction in the range of the upper limb hitherto primarily carried out using *PULMI* index.

2. Materials and methods

Method of calculation SDDI (The Standard Deviation of Differential Index)

The calculation algorithm of *SDDI* index (Standard Deviation of Differential Index) was developed as a supplement to the information provided by the *PULMI* index and it is an answer to the need to assess the similarity of the shape of the trajectory of angular waveforms of the studied person to the established pattern without considering the shift between these two trajectories. From a mathematical point of view the *SDDI* index is a value determining the standard deviation of the average distance value of the angular waveform from a movement pattern set based on the healthy people's moves.

SDDI indicates the irregularity of the movements of the upper limb associated with the difference of the shape of the time waveforms of anatomical angles in the joints from the adopted standard. A permanent distance, a permanent shift of the trajectory of the performed movement from the reference trajectory is counteracted here. The value of the $SDDI_r$ index is calculated for each of the N waveforms separately and then averaged accordingly to the relationship (1).

$$SDDI_r = \frac{1}{9}\sum_{k=1}^{9} SDDI_{r[k]} \qquad (1)$$

The coefficient shows the arithmetic mean of each of the calculated values $SDDI_{r[i\,\in\,\{1,\,...,\,9\}]}$ for the following upper limb movements:

- $SDDI_{r[1]}$ – flexion/extension of the upper section of the trunk around the sternoclavicular joint,
- $SDDI_{r[2]}$ – the rotation of the upper section of the trunk around the sternoclavicular joint,
- $SDDI_{r[3]}$ – abduction/adduction at the glenohumeral joint,
- $SDDI_{r[4]}$ – rotation in the glenohumeral joint,
- $SDDI_{r[5]}$ – flexion/extension the glenohumeral joint,
- $SDDI_{r[6]}$ – pronation/supination of the elbow joint,
- $SDDI_{r[7]}$ – flexion/extension of the elbow joint,
- $SDDI_{r[8]}$ – elbow adduction/radial abduction of the wrist joint,
- $SDDI_{r[9]}$ – palmar/dorsal flexion of the wrist joint.

Calculation of $SDDI_{r[i \in \{1, ..., 9\}]}$ for each of the waveforms requires calculating the average $SDDI_{\text{mean}}$ absolute value of the difference between the tested waveforms, and the reference waveforms for each of moments of time being under study, which is shown in the relation (2). The value of the $SDDI_{r[i \in \{1, ..., 9\}]}$ is the standard deviation for the calculated differences, which can be written as (3).

$$SDDI_{\text{mean}} = \frac{1}{m}\sum_{k=1}^{m}\left|f(k) - TD(k)\right| \tag{2}$$

$$SDDI_{r[i \in \{1,...,9\}]} = \sqrt{\frac{1}{m}\sum_{k=1}^{m}\left(\left|f(k) - TD(k)\right| - SDDI_{\text{mean}}\right)^2} \tag{3}$$

where:

$SDDI_{\text{mean}}$ – averaged absolute value of the difference between the waveform tested, and the reference waveform calculated for all the moments of time,

$f(k)$ – the value of one of the nine measured angle waveforms for the k-th time period,

$TD(k)$ – averaged (for the entire group of healthy people angular) value of one of the nine measured angle waveforms for the k-th period of time,

m – the length of the vector of each of the nine measured angle waveform which is 201 (0 to 100 with step of 0.5).

The lower value of the $SDDI_{r[i \in \{1, ..., 9\}]}$ index the more accurate the reflection of the shape of the movement, within the i-th joint, in relation to a motion pattern, which is the average of the angle waveform in the i-th joint for a selected group of healthy people. The lower value of the calculated SDDI_r index, the bigger resemblance of the shapes of the angle trajectory of the performed movements for all the joints to the established motor pattern. In order to compare the results of the SDDI index calculation with other parameters (e.g., the *PULMI*) its value was scaled in a manner identical to the *PULMI* index according to the relation (4).

$$SDDI = 100 - 10\frac{SDDI_r - SDDI_{r.TD.\text{mean}}}{SDDI_{r.SD.\text{mean}}} \tag{4}$$

where:

$SDDI_{r.TD.\text{mean}}$ – arithmetic mean value of $SDDI_r$ calculated for healthy people,

$SDDI_{r.SD.\text{mean}}$ – standard deviation values of $SDDI_r$ calculated for the group of healthy people.

SDDI index can be interpreted similarly to the *PULMI* index, that is, the closer to 100, the more the shape of the measured waveform resembles the shape of the adopted standard. Each reduction of about 10 points below 100 is the deviation of one standard deviation from the pattern of movement.

Comparative analysis of the obtained PULMI and SDDI for hypothetical waveforms

In order to determine the differences in the values taken on by the *PULMI* and *SDDI* indices and to indicate how to interpret the *SDDI* results, a series of waveforms with known functions describing them (waveforms models) and waveforms deviating from the standard, also with known functions describing them were developed.

The established pattern was calculated based on the five waveforms, marked in Fig. 1 in green and described by the following functions:

$$y_1 = 60 \sin(2\pi\, n/N) + 50,$$

$$y_2 = 50 \sin(2\pi\, n/N) + 50,$$

$$y_3 = 40 \sin(2\pi\, n/N) + 50,$$

$$y_4 = 60 \sin(2\pi\, n/N) + 60,$$

$$y_5 = 60 \sin(2\pi\, n/N) + 40.$$

where n is the value of consecutive (time vector, n = 1, 2, 3, ..., N), and N is the total number of waveform samples – 201 samples were established from 0 to 100 with step of 0.5.

The waveforms slightly differ from one another so that the standard deviation value calculated for the motion pattern does not equal zero (which occurs naturally in case of measurements). Otherwise it would be impossible to divide by this value, and thus to calculate the relations enabling the normalization and constituting an important step of calculation algorithms of proposed indices.

Various waveforms deviating from the established pattern, which are described by the following formulas, were considered:

A. $y_{tested} = 50 \sin(2\pi n/N) + 50$ – the waveform coincides with one of the standard waveform,
B. $y_{tested} = 50 \sin(2\pi n/N) + 65$ – the waveform is shifted along the value axis,
C. $y_{tested} = 50 \sin(2\pi n/N) + 35$ – the waveform is shifted along the value axis,
D. $y_{tested} = 50 \sin(2\pi n/N - 0{,}3) + 50$ – the waveform is shifted along the time axis,
E. $y_{tested} = 50 \sin(2\pi n/N) + 50 + 20 \sin(20\pi n/N)$ – the waveform with disturbances,
F. $y_{tested} = 10 \sin(2\pi n/N) + 50$ – the waveform with reduced amplitude,
G. $y_{tested} = -n + 100$ – the waveform significantly abnormal,
H. $y_{tested} = 50 \cos(2\pi n/N) + 50$ – the waveform of inverted phase,

These waveforms in Fig. 1 are shown in blue line. For such prepared waveforms functions *PULMI* and SDDI were determined and the results are shown in Fig. 1

The calculated values were also presented in graphs in Fig. 2.

For the A waveform where the angular values of the waveform coincide with one of the standard waveforms, the designated indices exceed 100 points. Slight shift of the tested signal along the axis of values, such as the one in examples B and C, influences the reduction of the *PULMI* index, but does not affect the value of the *SDDI* index. The same results for the indices were obtained for the shift of the same absolute value in both directions – of smaller and larger values. Shift along the time axis, as the one in example D, reduces

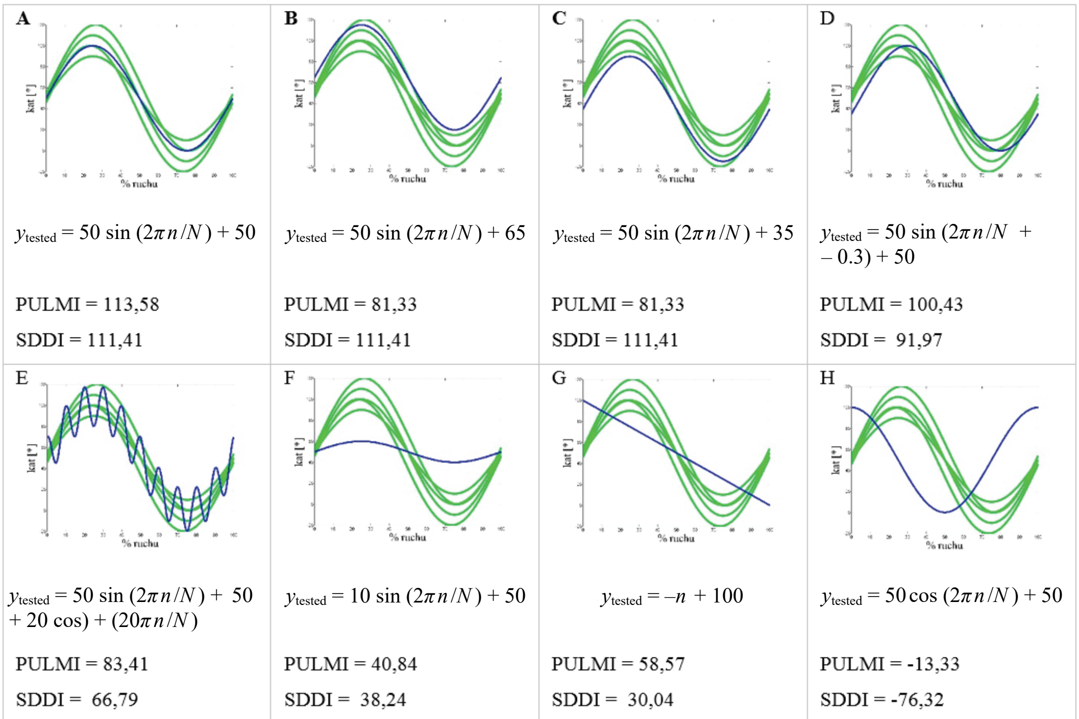

Fig. 1. Calculated values of *PULMI* and *SDDI* for assumed waveforms, blue colour indicated the waveform for which coefficients were calculated, green marked waveforms representing the waveforms of the reference group

Fig. 2. Calculated values of PULMI and SDDI for the assumed waveforms from A to H

both indices, and the lower value was reported for the *SDDI* index. Angular vibration imposed on the tested signal, as in example E, which caused a decrease in the value of both indices; reduction of the value was recorded for the coefficient *SDDI*. The reduction in signal of test amplitude as in example F resulted in a reduction of values of both indices. Similarly in example G, the use of angular waveform of a different type results in reduction of the value of the proposed indices. The lowest ratios of indices were obtained in example H where the tested signal was significantly shifted in phase and had different edge values.

Discussion for comparative analysis

The presented analysis clearly indicates which deviations from the standard waveforms have influence on both indices analysed. *PULMI* Index primarily enables noting the changes in the range of the movement (B and C) and the scope of the movement (F and G). While index *SDDI* is sensitive to the changes in the phase of the performed movement (D), the change in the trajectory of the movement (curve's shape) in such way, however, that the minimum and maximum values are in the range describing healthy people (E) – for example, trembling limbs, and the change in the range of motion (F and G). Addition of the analysis of the SDDI index to the *PULMI* analysis can be a valuable complement supporting the diagnosis and tracking the progress of rehabilitation, because when analysing the results of kinematic measurements one should pay attention not only to the changes in the scope of movement, but also to the phase shift. The interpretation of the results done this way will prevent disregarding some significant changes in the patient's medical condition.

Using *PULMI* index in the context of diagnosis along with the measuring systems of Motion Capture type one must pay special attention to the correct calibration of these systems. Improper calibration may affect the gained *PULMI* index value, because a shift of the measured values in relation to the values taken as a reference (as in the case of Fig. 1B and C) may occur.

Practical application of PULMI and SSDI

The analysis of the possibility of applying the *SDDI* index in practice was carried out on a group of healthy people (the reference group) and three people with mobility impairments of the upper limbs.

The study comprised a group of 23 healthy people (10 women: k1–k10 and 13 men: m1–m13) and a group of 3 people with mobility impairments (p1–p3). In the case of healthy people there were no observable and diagnosed defects within the upper limbs. Detailed data concerning the group of healthy people and the average values for the test group are given in Table 1. Table 2 describes the anthropometric characteristics of the patients.

Table 1. Characteristics of a group of 23 healthy people performing exercises according to the designed system

	Age	Weight [kg]	Growth [cm]	*BMI**
Mean	23.35	66.00	175.87	21.23
SD	1.37	11.76	9.48	2.61

* *BMI* – Body Mass Index.

Table 2. Characteristics of the patients tested

No.	Subjects	Age	Weight [kg]	Growth [cm]	BMI*
1	p1	17	54	167	19.4
2	p2	15	37	158	14.8
3	p3	41	72	176	23.2

* *BMI* – Body Mass Index.

Patient p1 was diagnosed with the malfunction of the skeletal and muscle system as a result of mechanical trauma of the peripheral nerves of the left limb (among other broken ulnar and radial nerves). As a result of injury the patient had problems with performing movements with the left wrist joint and left elbow joint. The lifting movement was limited and, in extreme cases, painful. The patient p2 suffered from cerebral palsy, which manifested in muscle spasticity of both upper limbs. He performed movements with great difficulty, and not in an accurate way. Ailment of the patient p3 included damage to the upper part of the left brachial plexus, which resulted in difficulties in performing movements of the left upper limb (there were slight movement restrictions within the elbow joint of this limb and inability to lift the arm above the head resulting from the restrictions of movement in the shoulder joint). The left limb was dexterous.

Selected pattern motions

For this study a sequence of movements was selected, with reference to Gzik's earlier studies [7] during which the kinematic value made by time values of anatomical angles in joints was measured. A person doing exercises was in the initial position with one arm raised (the left arm was assumed), as shown in Fig. 3a and then started straightening the left arm at the shoulder joint, at the same time bending the right arm at the shoulder joint, as shown in Fig. 3b until the position shown in Fig. 3c was reached. Then, after a pause, each limb moved opposite was similarly to the first part of the exercise until the initial position shown in Fig. 3e was reached.

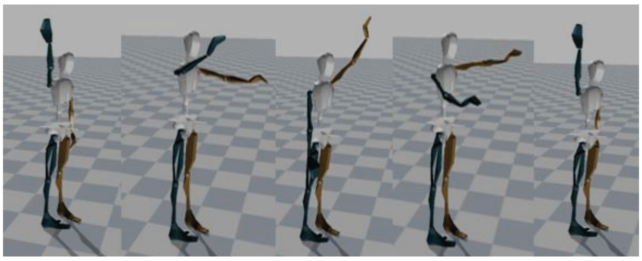

Fig. 3. Sequence of movements

People involved in the measurements were asked to make the moves in a continuous manner with a short break in the middle of the sequence of each of the movements synchronized with the beats of the metronome.

Data collection

The registration of the kinematic values was done using an inertial system for movement analysis MVN Biomech by Xsens. The study used the part of the system dedicated to the upper limbs, which consisted of 17 IMU (Inertial Measurement Unit) sensors fastened with armbands to the upper limbs (4 sensors on each limb) and the torso. Measurements made with the use of this system enabled the determination of the waveform changes in the values of anatomical angles of joints of both of the limbs. Every person analyzed did three repetitions of tested sequence of moves. The values of the kinematic magnitudes obtained were further analyzed in Matlab program. The results were subjected to decimation to 201 samples, so that each of the samples corresponded to the percentage rate of movement along the horizontal axis in steps corresponding the 2% of the move. Data prepared that way were used to calculate *PULMI* and *SDDI* indices.

3. Results

The results of the measurements for a selected activity are waveforms of nine anatomical angles in 4 joints of the each upper limb, according to Table 3.

Table 3. Measured values together with the corresponding acronym

1	flexion/extension of the upper section of the trunk around the sternoclavicular joint	sc.fe
2	the rotation of the upper section of the trunk around the sternoclavicular joint	sc.r
3	abduction/adduction at the glenohumeral joint	gh.aa
4	rotation in the glenohumeral joint	gh.r
5	flexion/extension the glenohumeral joint	gh.r
6	pronation/supination of the elbow joint	e.ps
7	flexion/extension of the elbow joint	e.fe
8	elbow adduction/radial abduction of the wrist joint	w.rdud
9	palmar/dorsal flexion of the wrist joint	w.fe

In the first phase the values of *PULMI* and *SDDI* for the measured waveforms were calculated and then averaged for all three measurements. The results are presented in Tables 4 and 5.

Table 4. Mean values of *PULMI* index for the analysed sequence of movements

		Group of healthy subjects		p1	p2	p3
		Mean	SD			
Left limb	*PULMI*	100.00	10.00	63.07	67.12	72.11
Right limb	*PULMI*	100.00	10.00	91.84	49.96	86.30

Table 5. Mean values *SDDI* index for the analysed sequence of movements

		Group of healthy subjects		p1	p2	p3
		Mean	SD			
Left limb	*SDDI*	100.00	10.00	91.33	71.63	89.17
Right limb	*SDDI*	100.00	10.00	95.79	69.39	90.51

Next, in order to make a more detailed analysis of the factors influencing the values of *PULMI* and *SDDI*, based on the results obtained for healthy people, the scientists developed a standard of waveform changes in time of anatomical angles for all movements measured as the range from the mean value minus a standard deviation to the mean value plus a standard deviation. The waveform changes of the same angles obtained from measurements of patients p1–p3 and the respective standards are shown in Fig. 4.

In the next step, basing on a subjective, comparative analysis of graphs of changes of joint angles obtained from patients and on standards, it was determined which movements in the patients' various joints can influence the reduction of *PULMI* and *SDDI* indices. For *PULMI* index the waveforms reducing the

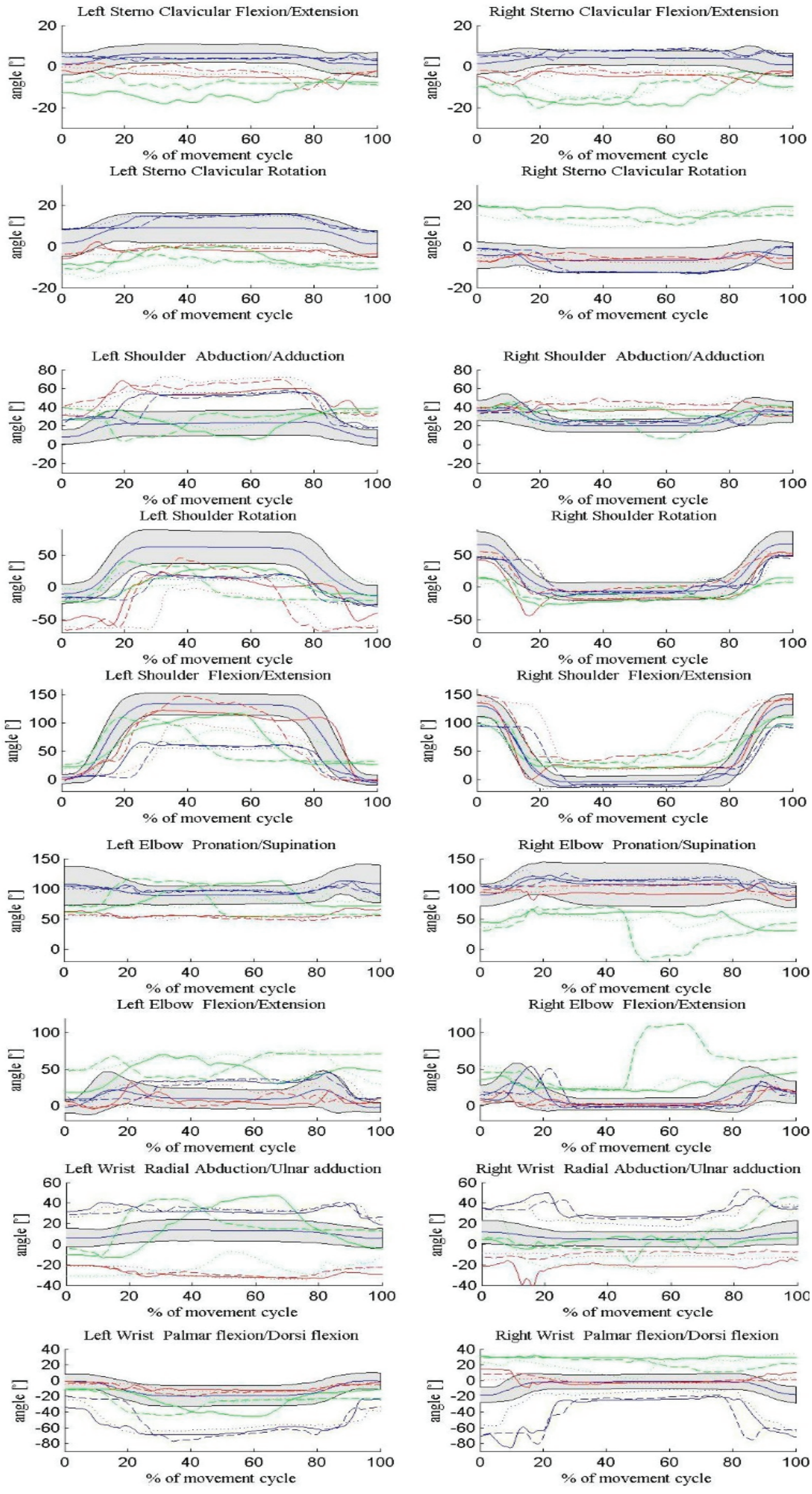

Fig. 4. The waveforms of anatomical angles in joints for the three patients with the motion problems in the upper limb compared with the standards obtained for healthy people. In red color are waveforms for p1, green for p2, and in blue color for p3

Table 6. Waveforms that affect the reduction of the *PULMI* index
based on the analysis of index calculation and compared with the standard adopted

	Number of waveforms which can reduce the value of the *PULMI* index					
	p1		p2		p3	
	Sequence of motion	Number of moves	Sequence of motion	Number of moves	Sequence of motion	Number of moves
Left limb	sc.fe, sc.r, gh.aa, e.ps, w.aa	5	sc.fe, sc.r, gh.r, e.fe, w.aa	5	sc.r, gh.aa, gh.fe, w.aa, w.fe	5
Right limb	gh.aa, w.aa	2	sc.fe, sc.r, gh.aa, e.fe, e.ps, w.fe	6	w.aa, w.fe	2

Table 7. Waveforms that affect the reduction of the *SDDI* index
based on the analysis of index calculation and compared with the standard adopted

	Number of waveforms which can reduce the value of the *SDDI* index					
	p1		p2		p3	
	Sequence of motion	Number of moves	Sequence of motion	Number of moves	Sequence of motion	Number of moves
Left limb	w.aa	1	sc.fe, gh.fe, e.ps, e.fe, w.aa	5	gh.aa, e.fe	2
Right limb	gh.aa	1	sc.fe, gh.aa, e.ps, e.fe	4	sc.r, sc.r	2

value of this index were those shifted along the value axis (vertical axis) and those significantly deviating from the average value (waveforms with large differences between the values of the angles for the same moment in time). For *SDDI* index the waveforms affecting the change in the value of this index were those with a large discrepancy in shape compared to the value adopted as the standard. The results, together with highlighting the waveforms, that have been identified as significantly different and which affect the values of the indices, are presented in Tables 6 and 7. The increment of the number representing the number of movements regarded as those influencing the changes in the value of indices occurs when at least one of the three measured waveforms for a given move in the joint differs significantly from the average standard.

Table 8. Values of correlation coefficients
between indexes values and the number of existing waveforms
which can reduce the value of the indexes

		Index	
		SDDI	*PULMI*
Index of correlation	Spearman's	–0.912159	–0.925820
	Kendal's	–0.787726	–0.856349

In order to determine whether there is a statistically significant correlation between the number of abnormal waveforms and *SDDI* and *PULMI* indices, the correlation (using Spearman and Kendal coefficients) between these values was calculated. The analysis was carried out using STATISTICA software, and the results are shown in Table 8. The results proved a strong correlation between all the analysed values.

In order to investigate the occurrence of the linear relationship between the number of failures in the values of indices, the obtained data were shown in the graphs and then a linear regression was defined and the value of R^2 coefficient (coefficient of determination). The obtained data are shown in diagrams.

The obtained values of R^2 of 0.9 prove that the points were well matched with the designated curve, which shows the linear dependence of the number of failures on the index value.

4. Discussion

Calculated values of PULMI and SDDI indices (Tables 6 and 7) show the level of physical dysfunction in the area of the upper limbs for patients undergoing the tests in relation to the performed sequence of movement. For both indices the values above 90 points correspond to properly performed sequence of movements and each drop of about 10 points below 100 points means one standard deviation change from the correct movement pattern.

For the patient p1 the value of *PULMI* index is by about 29 points lower for the left limb (63.07 points) than for the right limb (91.84 points). Reduced value indicates the presence of motor dysfunction in the left limb, what was confirmed by clinical assessment. The calculated values of the *SDDI* index for patient p1 are 91.33 points for the left limb and 95.79 points for right limb, which indicates no motor dysfunction that would be reflected in irregularities in the execution of movements, associated with the shape of the obtained angle trajectory. Analysing both values obtained by the *PULMI* and *SDDI* indices can indicate the right limb as a healthy one and the left limb as the one with motor dysfunction, which is reflected in a shift of the angular ranges along values when performing the given sequence of movement. Taking into account the global motion in all joints, the values of both indices can be interpreted in such way that during making movements with that limb the patient keeps ranges of motion (change of range of motion would cause a simultaneous decline in both indices). Secondly, there is none or little shift of movement in the phase (indicated by *SDDI* index) which means that the trajectory of the movement has been preserved. Moreover, there may be changes in angular range of the movement – a shift of the trajectory of the performed move into higher or lower angular ranges than normal (indicated by a decrease of *PULMI* index).

Analysis of angular waveforms (Fig. 4) and pointing out the movements which influence the values of the indices confirm the assumptions described above. The ranges of the performed movements are close to normal, but the selected movements in the certain joints are performed in ranges outside the scope accepted as standard.

For the patient p2, who had clinically confirmed motor dysfunction in both upper limbs, the *PULMI* index is 67.12 points for the left arm and 49.96 points for right arm. The values of *SDDI* indices are 71.63 points for the left arm and 69.39 points for right arm. The obtained values indicate the presence of motor dysfunction in both upper limbs, but the level of dysfunction is greater for right limb, because the values of *PULMI* and *SDDI* are lower than for the left limb. Analysing both indices it can be stated that there might be changes in the ranges of movements (fall in the value of both indices). Secondly, a shift in the phase of performing some moves or change in the shape of the trajectory (decrease of *SDDI*), and tremors of limbs may occur (decrease of *SDDI*). Moreover, part of the movements can be performed outside the ranges assumed as correct ones (decrease of *PULMI*).

The above conclusions were deduced from the waveform diagrams of changes of joint angles (Fig. 4). In the case of this patient the irregularities in the execution of movements and suspicious vibrations of the upper limb during performing of the sequence of movements were noted, which was confirmed by observations of the angle trajectory in Fig. 4. Waveforms for patient p2 are located mostly outside the ranges accepted as the norm, and, in the case of pronation and supination in the right elbow joint do not resemble the shape of the average waveform assumed as the standards. The results for patient p2 who suffers from cerebral palsy are within the scope of the results obtained by Butler [2] for this type of diseases. In addition, the values of waveforms that affect the reduction of *PULMI* and *SDDI* indices (Tables 4 and 5) are in the range from 5 to 6 for the *PULMI* index and from 4 to 5 for the *SDDI* index, which also points out the deficiencies in the performance of the given sequence of movement.

In the case of patient p3 a slight reduction of the SDDI index in both limbs (89, 17 left and 90.51 right) can be noticed, while the *PULMI* index has a value 72.11 for the left limb and 86.30 for the right limb. These values may indicate the change in the scope of performing certain moves (drop in the value of both indices) and in the range of the performed movement – performing the move outside the ranges given as standard (reduction of the *PULMI* index), and possible slight tremor of the limbs.

The analysis of angle waveforms (Fig. 4) confirms the above analysis. The move of the right limb is close to normal. Only in the wrist joint it is outside the range accepted as standard. In the left limb there are more anomalies of a similar nature (shoulder joint), which results in reduction mainly of *PULMI* index (change in the range of the movement together with the slight change of movement range).

Comparison of calculated values of *PULMI* and *SDDI* indices showed in Tables 6 and 7 with the number of waveforms which affect the reduction of indices shown in Tables 4 and 5, is highly correlated with both *SDDI* and *PULMI* indices. The results of calculations of the Spearman and Kandal's coefficients of correlation are presented in Table 8.

A strong correlation between the values of indices and the number of failures that affect the reduction of values of the indices can be also observed based on Fig. 5, where additionally the course of the linear regression was drawn. The calculated value of R^2 (coef-

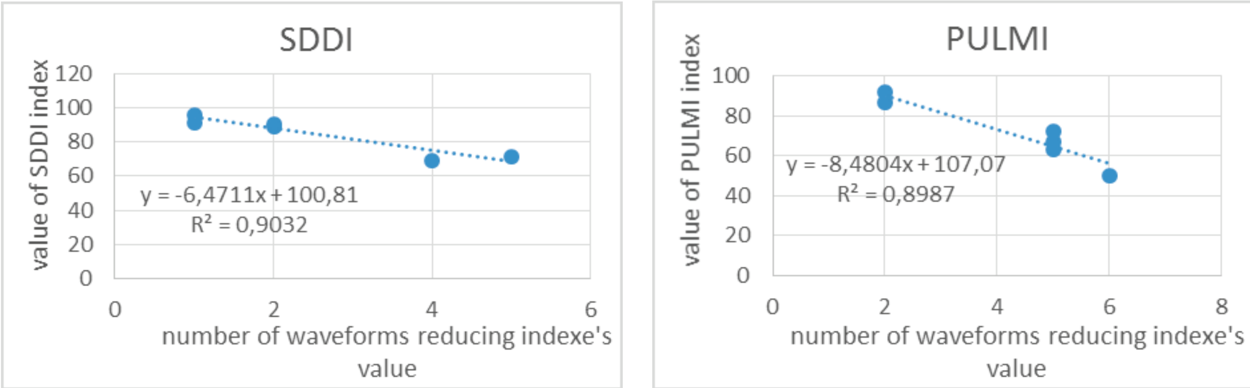

Fig. 5. The charts showing the relationship between the values of SDDI and PULMI indices depending on the number of waveforms which can reduce the value of the indexes

ficient of determination) for the linear regression is at the level of about 0.9 for both indices, which indicates a strong linear relationship between the number of waveforms, which contribute to a decrease in the values of *PULMI* and *SDDI* indices, and the calculated values of these indices.

5. Conclusions

The proposed new *SDDI* index is a tool for the objective assessment of motor dysfunction occurring in the upper limbs. It allows you to specify the severity of motor abnormalities associated above all with the change of the shape of the trajectory of the performed movement or shift in a phase of the performed movement. *SDDI* index also complements *PULMI* index with an assessment of how the movement was performed. Joint analysis of both indices provides information on whether the patient has correctly performed the given sequence of moves and enables the determination of the kind anomalies in the performance of a given movement.

Future research

The next step will be to test in clinical practice the methodologies to assess kinematics of the upper limb on the basis of the indexing method, using the *PULMI* and *SDDI* indices.

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