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The Upper Limb Motion Deviation Index: A new comprehensive index of upper limb motion pathology

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Purpose: The aim of the research was to formulate a new index enabling assessment of the overall pathology of the upper limb movement. It defines the difference between the pathological movement and a normal movement pattern. *Methods*: Methodology of determining the index is based on a mathematical algorithm for calculating the Gait Deviation Index which is based on advanced methods of image comparison. To calculate the ULMDI index, one must divide the analyzed movement into cycles appropriate to the nature of the movement (similarly in gait it is the gait cycle) and then determine kinematic quantities (courses of joint angles). *Results*: A group of 23 healthy people (10 women: k1–k10 and 13 men: m1–m13) as the reference group and a group of 3 persons with mobility impairments (p1–p3) took part in the research. Time values of the angles of the joints on both upper limbs were registered and then ULMDI indexes were calculated. *Conclusions*: It has been shown that the developed ULMDI index allows to detect the deviations from the accepted norm in the performance of movements. The results showed that both the description of the motor dysfunction of examined person based on the diagnosis of the physician, a detailed analysis of kinematic waveforms received during the tests and the calculated values provide a coherent picture of the state of a human movement. The index analysis is less time-consuming for the doctor, and the comparison of the results at various stages of therapy gives an objective picture of the rehabilitation progress.

Key words: *upper limb motion pathology, ULMDI, gait deviation index*

1. Introduction

A spatial analysis of motion is increasingly often being used to support the diagnosis, an assess the progress of treatment or rehabilitation plan. Thanks to modern measurement tools it is possible to determine the parameters of time and space, kinematics and dynamics of motion and the factors that enable objective evaluation [1], [3], [11]–[14]. Biomechanical studies of motion provide large amounts of measurement data in the form of timewaves which are difficult to interpret quickly by a doctor or physiotherapist. The analysis of data presented in this manner is a time-consuming process that requires a lot of experience. In order to simplify the interpretation of the results, indexing methods were developed, which allow for quick diagnostics on the basis of one or more numerical values [1], [10]. A single index value shows, in an overall way, the tested movement, specifying how much it differs from an average normal movement.

Indexing methods are used increasingly in medical facilities around the world to analyze the results of experimental studies of gait [6], [15], [19]. In the literature one can find plenty of information on research using the following indexes: Gillette Gait Index [21], Gait Deviation Index [22], GDI-Kinetic [20], Gait Profile Score [2]. The indexes mentioned above are calculated using different types of mathematical algorithms in which the input data are various sets of parameters such as time-space, kinematic and dynamic of motion.

As opposed to conducting a comprehensive study of gait, the researchers have only recently taken up the studies of the kinematics of the upper limbs [1], [3], [22]. The characteristic features of the movement of

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the upper limb include the lack of repeatability of cyclic movements, the complexity of movement in the joints and a large range of motion in the shoulder joint. Knowledge of ranges of motion in the joints of the upper limb and the time-space parameters (speed, duration, trajectory) can provide a great deal of important information on the quality of the movement [5], [8], [11], [25] to the diagnosis and treatment. Relevant information can also be obtained by observing reactions in the joints and muscles during specific activities [18], [24]. There are few studies related to the use of index methods in assessing the dysfunction of movement of the upper limbs. The attempts to build indexes based on the algorithms used in the analysis of gait have been reported only from 2011.

Jasper and co-workers in the work [8] proposed The Arm Profile Score index (APS) calculated on the basis of the difference in root mean-square (RMS) between a set of kinematic parameters of the person with disabilities in mobility of the upper limb and the average values of the parameters in a group of healthy individuals [2]. APS index takes into account 13 parameters defining the kinematics of the trunk, scapula, shoulder joint, elbow and wrist joints. The Arm Profile Score can be resolved into 13 AVS (Arm Variable Scores) variables representing the deviation of the individual parameters of movement of a person from average values obtained for the standard movement. The result of APS index with 13 AVS variables creates a profile of upper limb movement called a map of movement (A -MAP) [8].

A similar index also determined based on the difference in root mean-square (RMS), was created by Riad J. and co-workers [16]. Arm Posture Score Index was developed to assess the movement of the upper limb during gait of the patients with spastic form of cerebral palsy (hemiplegia). This index is based on four parameters, i.e., flexion/extension of the shoulder, elbow and wrist joints and adduction/abduction in the shoulder joint.

Another index used to assess the overall pathology of the movement of the upper limbs is The Pediatric Upper Limb Motion Index (PULMI) [4]. It was developed by Butler and Rose and is dedicated to children with various forms of cerebral palsy (spastic, dyskinetic and ataxic). The PULMI index is calculated based on 8 kinematic parameters of the upper limb, i.e., flexion/extension and axial rotation of the trunk, rotation of the hip joint, arm lifting, flexion/extension of the elbow joint, pronation/supination of the forearm, dorsal and plantar flexion and adduction/abduction of the wrist joint. PULMI provides quantitative information on the movement of the upper limb while reaching and grasping. Pediatric Upper Limb Motion Index, like the previous indexes, is built on the basis of the difference in root mean-square (RMS), though it is also scaled according to the method used in determining the Deviation Gait Index [2.22]. According to the authors, PULMI index can be used to assess the severity of the neuromuscular deficits of the upper limb and to monitor the effects of the treatment, i.e., to evaluate changes developed due to surgical intervention and rehabilitation [4].

To create the Arm Posture Score index the authors used four parameters determining the flexion and extension in the joints of the upper limb and adduction/abduction in the shoulder joint. While analyzing the motion of the upper limb during walking the number of parameters may be sufficient, analyzing other activities the number of parameters have to be increased taking into account the other movements in the joints. The compensation movements of the body must also be taken into consideration. Arm Profile Score Index takes into account 13 parameters, while for creating PULMI index, which evaluates the upper limb movement while reaching and grasping, 8 kinematic parameters proposed by Butler and co-workers were used [3]. The authors of the PULMI index in its structure did not take into account the movements of flexion/extension in the shoulder joint, and abduction/adduction in this joint. These excluded movements compose important parameters characterizing the movement of reaching and grasping which can vary significantly, particularly among patients with disorders/deficits of mobility of the upper limbs. The omission of these two parameters can cause that the assessment of the movement of the upper limb using this index can give an incomplete picture of dysfunction.

All indexes mentioned above were constructed on the basis of the root-mean square (RMS) difference between a set of kinematic parameters of the tested person and the average values of parameters for a group of healthy people. In contrast, McMulkin and co-workers in their work [10] indicated that the index calculated or scaled based on the GDI algorithm is the most sensitive measure of assessment of the differences before and after treatment comparing the results with the control group.

Therefore, the authors decided to attempt to build a new ULMDI index (Upper Limb Motion Deviation Index) based on a mathematical algorithm for calculating the Gait Deviation Index proposed by Schwartz and Rozumalski [22] in order to create intuitive and accurate measure of assessment of clinical changes. To build the index they decided to choose the right amount of kinematic parameters so that the index built on this basis gave the broadest aspect of the pathology of the movement of the upper limbs. Prepared index has been the first indicator of upper limb function built on the basis of the GDI algorithm which according to McMulkin co-workers' research, is currently the most reliable measure of differences in kinematics of the lower limbs before and after treatment [10].

The objective of the work is to develop a new index enabling objective assessment of kinematic motor deficits in the upper limb. Designed ULMDI index (The Upper Limb Motion Deviation Index) is a single, numerical value which clearly defines how motion of a patient differs from the normative values obtained for the control group of healthy people.

2. Materials and methods

2.1. Methodology of calculation ULMDI

Upper Limb Motion Deviation Index was introduced as a measuring device of the overall pathology of the upper limb movement. It defines the difference between the pathological kinematics motion and normal movement pattern. ULMDI methodology of determining the index is based on a mathematical algorithm for calculating the index of gait, Gait Deviation Index proposed by Schwartz and Rozumalski [22], which, in turn, is based on advanced methods of image comparison.

As in the case of GDI, in order to calculate the ULMDI index one must select the quantities on which it is calculated. This work proposes 9 such variables that fully describe the kinematics of motion of the upper limb:

- flexion/extension of the upper section of the trunk around the sternoclavicular joint (*sc.fe*),
- the rotation of the upper section of the trunk around the sternoclavicular joint (*sc.r*),
- abduction/adduction at the glenohumeral joint (*gh.aa*),
- rotation in the glenohumeral joint (*gh.r*),
- flexion/extension of the glenohumeral joint (*gh.fe*),
- pronation/supination of the elbow joint (*e.ps*),
- flexion/extension of the elbow joint (*e.fe*),
- elbow adduction/radial abduction of the wrist joint (*w.rdud*),
- palmar/dorsal flexion of the wrist joint (*w.fe*).

A single numerical value of ULMDI index evaluates the movement of one upper limb.

To calculate the ULMDI index, one must divide the analyzed movement into cycles appropriate to the nature of the movement (similarly in gait it is the gait cycle, the phase of the support, etc.). For as specified cycle of motion so called the motion vector of dimensions 459 × 1 is generated in the form of:

$$\mathbf{g} = [\{sc.r\}, \{sc.fe\}, \{gh.aa\}, \{gh.r\},$$
$$\{gh.fe\}, \{e.ps\}, \{e.fe\}, \{w.rdud\}, \{w.fe\}]^T$$
$$= [\{g_{1-51}\}, \{g_{52-102}\}, ..., \{g_{(358-408}\}, \{g_{409-459}\}]^T, \quad (1)$$

where:

n – the number of samples per single cycle of motion, it was assumed $n = 51$ – It is based on the sampling frequency (reading of the measured values) every 2%, where the range 0% to 100% means the entire motion cycle,

$[\ ]^T$ – means transpose matrix.

The dimension of **g** vector results from the fact that the entire movement cycle is regarded as 100% and the results of every 2% of total growth of the cycle are taken into consideration. As a result for the 9 angle parameters, which are set 51 times during a single cycle, one obtains 459 data.

The **g** vectors, defined in this way, are determined for the group of healthy people (control group) and patients with motor dysfunctions in the upper limbs and are joined in the matrix of motion **G** of size $n \times N$:

$$\mathbf{G} = \begin{bmatrix} \mathbf{g}_1^1 & \mathbf{g}_1^2 & \cdots & \mathbf{g}_1^N \\ \mathbf{g}_2^1 & \mathbf{g}_2^2 & \cdots & \mathbf{g}_2^N \\ \vdots & \vdots & \cdots & \vdots \\ \mathbf{g}_{9n}^1 & \mathbf{g}_{9n}^2 & \cdots & \mathbf{g}_{9n}^N \end{bmatrix}, \quad (2)$$

where:

n – the number of data obtained in a single cycle of movement of the upper limb,

N – total number of analyzed waveforms in selected cycle of motion (altogether for the control group and patients with dysfunctions in the upper limb).

The initial columns of the matrix include motion vectors for the control group. After that the motion vectors of patients with disorders of manual functions of the upper limb are added.

The next step in calculating the ULMDI index is singular value decomposition (SVD) of the matrix **G** maintaining the unitary length of individual eigenvectors $\{\hat{\mathbf{v}}_1, \hat{\mathbf{v}}_2, \hat{\mathbf{v}}_3, ..., \hat{\mathbf{v}}_{9n}\}$ and the individual eigenvalues $\{\lambda_1, \lambda_2, \lambda_3, ..., \lambda_{9n}\}$ as marked in the literature [6].

Then one determines the components of a motion vector projected on k directions c_k, the reconstructed motion vector $\mathbf{g}^{\sim m}$ and the Euclidean distance $d^{\propto,TD}$ between the reconstructed vector of movement of the tested person α and the average motion parameters in the control group TD. Choosing the right reconstruction m allows for receiving the value $\mathbf{g}^{\sim m}$ close enough to the value of $\mathbf{g}$. For this purpose two independent criteria VAF_m and φ, precisely defined in the work by Schwartz and Rozumalski [20], were used:

$$c_k = \mathbf{g} \cdot \hat{\mathbf{v}}_k , \quad (3)$$

$$\mathbf{g}^{\sim m} = \sum_{k=1}^{m} c_k \hat{\mathbf{v}}_k , \quad (4)$$

$$d^{\propto,TD} = \| c^{\alpha} - c^{-TD} \| . \quad (5)$$

With the Euclidean distance between the tested person α, and the control group TD one should determine a so-called "raw" index ULMDI (raw ULMDI) for the tested person α, which is defined as:

$$ULMDI_{raw}^{\propto} = \ln(d^{\propto,TD}) . \quad (6)$$

The final step aimed at producing high-quality ULMDI index is scaling. Then it is necessary to calculate $ULMDI_{raw}^{k}$ for each person in the control group (TD) according to the following formula:

$$ULMDI_{raw}^{k} = \ln(d^{k,TD}) = \ln(\| c^{k} - c^{-TD} \|) . \quad (7)$$

Then with all the results $ULMDI_{raw}^{k}$ obtained for healthy individuals one must calculate a mean value Mean($ULMDI_{raw}^{TD}$) and standard deviation S.D.($ULMDI_{raw}^{TD}$). In further step, in order to determine the index values for the individual α with dysfunctions in the upper limbs, one must determine the z-score of $zULMDI_{raw}^{\propto}$ in relation to the control group TD according to the formula:

$$zULMDI_{raw}^{\propto} = \frac{ULMDI_{raw}^{\propto} - \text{Mean}(ULMDI_{raw}^{TD})}{\text{S.D.}(ULMDI_{raw}^{TD})} . \quad (8)$$

The obtained final result should be scaled according to the following relation:

$$ULMDI^{\propto} = 100 - 10 \times zULMDI_{raw}^{\propto} . \quad (9)$$

The value of ULMDI index calculated in this way allows you to determine in a numerical way the degree of similarity of the tested movement in relation to the average movement (performed by people from the control group) adopted as a model.

When the obtained value of the value of the index ULMDI $\geq$ 100 – it means that the movement is close to correct and, therefore, it is not pathological.

In contrast, any reduction in the index of 10 means that the kinematic motion of the tested person is distant by one standard deviation from the kinematics of the control group [22]. For example, when $ULMDI^{\propto}$ where α is 73 points then the movement of the tested person is 2.7 × S.D.($ULMDI_{raw}^{TD}$) distant from the movement adopted as a model.

2.2. Interpretation of the index

ULMDI index value is interpreted as the scale of similarity of the tested movement in relation to the adopted reference pattern without pointing out where these differences are and how individual courses and parameters influence value of the index. Therefore, similarly to the GDI index for a gait, the ULMDI index may be used, for example, to determine the overall level of common dysfunctions of the upper limb or, by comparing the results obtained at different stages of rehabilitation, indicate to what extent to treatment improves the motor abilities of the patient. This index, similarly to the GDI, thanks to the algorithm based on the correlation assessment make it possible to make an overall assessment of the compared waveforms without designating the special features.

In order to describe the interpretation possibilities of ULMDI index in a better way, an analysis of changes in the value of this index at various deviations from the norm was prepared. For this purpose, a hypothetical motion model based on 5 waveforms described by the following features was made (Graph 1, green waveforms):

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

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

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

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

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

where n is consecutive waveform samples (vector time, n = 1, 2, 3, ..., N), and N is the total number of waveform samples (it was estimated to have 201 samples from 0 to 100 with steps of 0.5).

Some minor differences between the particular model waveforms were introduced so that the standard deviation calculated for the motion pattern would not equal zero. Otherwise it would be impossible to divide by this value and, consequently, to calculate the index. Then 8 different waveforms were generated, which more or less diverge from the accepted standard (blue waveform). For each of these 8 waveforms ULMDI index was calculated. Graph 1 from A to H shows the reference waveforms and the analyzed case of disturbed waveform. The waveform A is the same as the model waveforms and the calculated ULMDI index is 115.14. The vertical shift of the waveform by a fixed value (equal 15) up or down (Graphs B and C) without changing the shape of the waveform, lowers the ULMDI index to less than 87. A similar value was also obtained in the case of oscillation of the disturbed waveform between the minimum and maximum values of standard waveforms (Graph E). A slight shift of the graph disturbed in time compared to the model graph with the shape preserved and similar to standard waveforms (Graph D) affected the value in a very slight way. However, significant aberration was observed with bigger disorders. ULMDI values for waveforms substantially flattened in relation to the standard, were 75 and 78, while for the graph with a similar extent as the reference but with reversed phase the rate reached its lowest among the analyzed ones and it was 66. However, analyzing the described waveforms it should be remembered that this is only an example of a description of possible changes in the index. As mentioned previously ULMDI index is calculated on the basis of 9 selected waveforms of kinematic values and, by assumption, it does not give answers which of these 9 factors and to what extent affect its value but only indicates in a general way the efficiency of the tested limb.

2.3. Practical applications

In order to check the suitability of developed index the study was conducted both on healthy people and those with disorders. The study was conducted for a sequence of movements of the upper limbs selected by a therapist. The selected movement (Fig. 2), which refers to big graphomotor abilities, is one of the standard rehabilitation exercises performed in clinical therapy for diagnostics and rehabilitation of the upper limbs.

Participants

A group of 23 healthy people (10 women: k1–k10 and 13 men: m1–m13) as the reference group and a group of 3 people with mobility impairments (p1–p3) took part in the research. The examined healthy individuals had properly developed musculoskeletal system and they had no observable and diagnosed defects

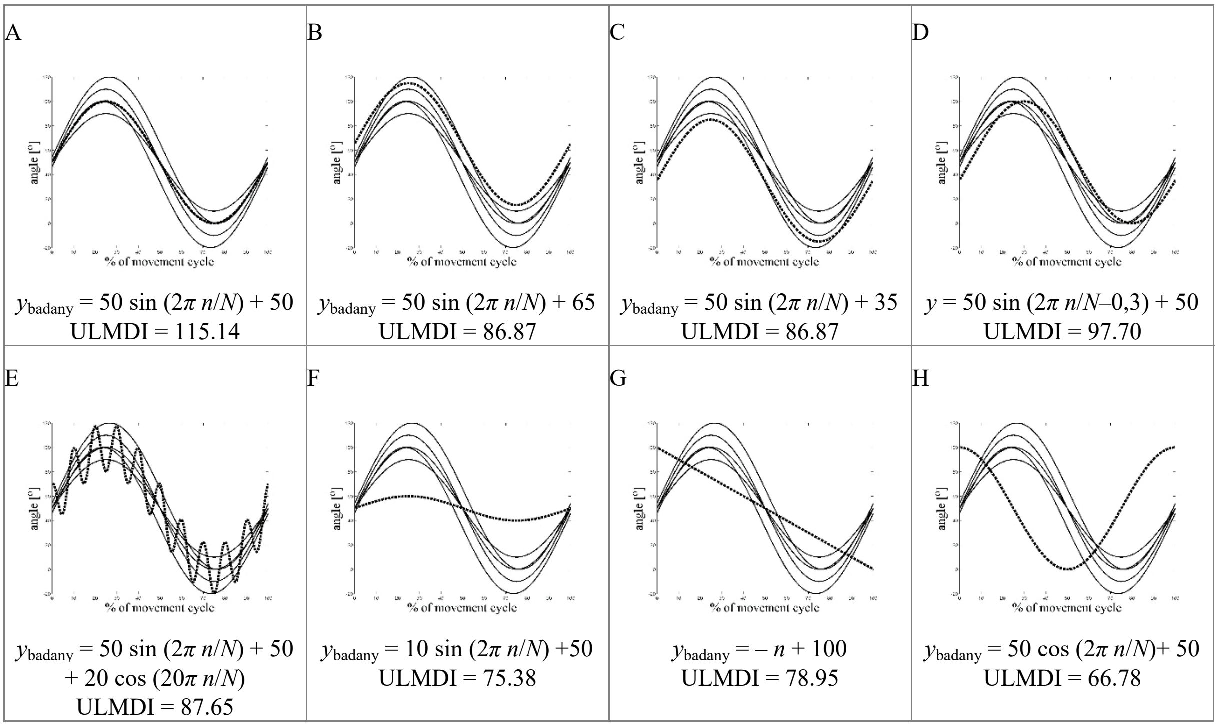

Fig. 1. Calculated values of ULMDI index for assumed waveforms.
Blue color indicates the course for which coefficients were calculated,
green shows waveforms representing the waveforms of the reference group

Table 1. Characteristics of the group of 23 healthy people performing exercises in the designed system

	Age	Wei,ght [kg]	Hei,ght [cm]	BMI*
Average	23.35	66.00	175.87	21.23
SD.	1.37	11.76	9.48	2.61

Table 2. Characteristics of all tested people

No.	Subject	Age	Weight [kg]	Height [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				

within the upper limbs. Detailed data of a group of healthy people and the average values for the test group are given in Table 1. Tables 2 and 3 describe the anthropometric characteristics and dysfunctions of the patients.

Information about the dysfunction of the first patient p1 includes a malfunction of the skeletal and muscle systems which was a result of mechanical trauma to peripheral nerves of the left limb (damaged to the ulnar and radial nerve). The injury occurred when the patient was about 15 years old and since then the tested person had problems with the movements of the left wrist and left elbow joints. Their movement is limited and causes pain in extreme cases.

The second patient (p2) suffered from cerebral palsy which manifested in muscle spasticity in both upper limbs. Patient performed movements with great difficulty, what makes them very inaccurate.

Ailment of the third patient (p3) comprises damage to the top of the brachial plexus. The injury occurred after the age of 20. The right limb is dexterous. The patient had difficulties in performing movements of the left limb, such as small restrictions of the movement of the elbow left joint and inability to lift the arm above the head resulting from the restrictions of movement in the shoulder joint.

Selected pattern motions

The selected sequence of motion consists of alternating lifting and lowering the limbs. A person performing the exercises starts from the initial position with one hand raised (it was assumed that this is the right hand) as shown in Fig. 2a, and then performs extension of the left limb in the shoulder joint, mutually with flexion of the right limb at the shoulder joint, as shown in Fig. 2b, until the position of Fig. 2c is reached. Then, after a pause, each limb moves opposite similarly to the first part of the exercise as far as initial position of Fig. 2e is reached.

(a) (b) (c) (d) (e)

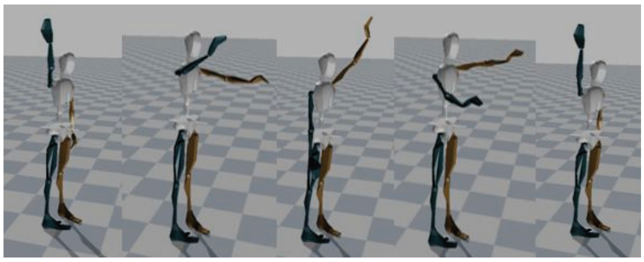

Fig. 2. Sequence of motion. The first phase – movement from "a" to "c" maintenance phase – the position "c", the second stage of movement – a movement from "c" to "e"

Individuals performing the exercises involved in the measurements were intended to perform the movement continuously with a short break in the middle of each sequence of movements.

The sequence of movements has also been divided into two phases: the first one – the movement of descent for the right limb and lifting the left limb (Fig. 2a–c) and the second phase – a movement of lifting the right limb and descending of the left limb (Fig. 2c–e).

Data collection

Changes of courses of the angles of the joints on both upper limbs in time were registered (with frequency 120 Hz) with the use of an independent inertial MVNBiomech system of Xsenss company and were entered into the original Calculate ULMDI application developed in Matlab environment where they were subjected to further analysis. For each of the tested person three repetitions of the tested sequences of motion were registered. The results were subjected to a decimation to 51 samples so that each of the samples corresponded to the percentage rate of movement along the horizontal axis with steps of 2% of the motion. The results of computed reconstruction accuracy was 99% for m = 15 features, measured by variance accounted for (VAF) and reconstruction fidelity (φ). There criterions were precisely defined in the work by Schwartz and Rozumalski [20]. The analysis of the results comprised calculations of all angular values for all tested joints of the upper limb of every examined person. The time waveforms of angular values were also divided into phases, as described earlier (Fig. 2).

3. Results

On the basis of the developed algorithm necessary calculation to prepare a calibration results were done. Next, the ULMDI indexes for healthy people and patients with mobility impairments were set.

The obtained results of ULMDI index value, divided into right and left limbs for 23 healthy people, are shown in the histograms of Fig. 3.

According to the adopted calculating algorithm for healthy people the average value is 100 points and standard deviation is 10 points.

3.1. Test results for people with mobility impairments

In the next step the calculations of ULMDI index for people with mobility impairments were done taking a group of healthy individuals as a model of properly performed movement sequences. The calculated results are presented in Table 3.

3.2. Analysis of results

For the first patient (p1) an increase by at least 12 points of ULMDI coefficient was noted for the right limb (healthy). For the second patient (p2) low coefficient values of ULMDI for the right limb and slightly larger value for the left limb were noted. However, these values are less than 90 points for both limbs, which indicates possible dysfunctions in the right and

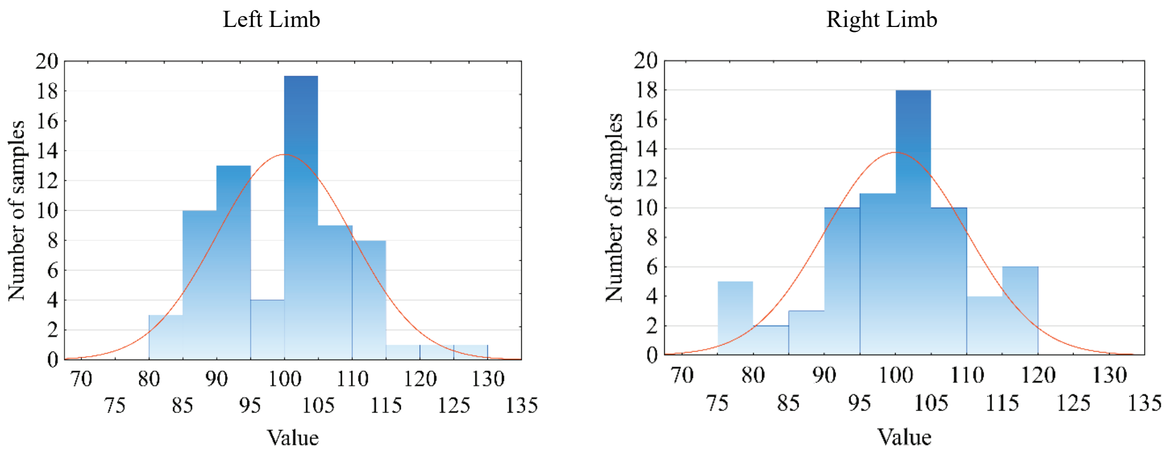

Fig. 3. Histograms of the obtained ULMDI index value for a group of healthy people

Table 3. The results of calculated index value for patients with motor dysfunction of the upper limb (blue colour – results for limbs with motor dysfunction, gray color – results for the limbs without dysfunction)

		Calculated ULMDI index		
		p1	p2	p3
Full motion	Left Limb	74,53	76,31	76,53
	Right Limb	90,75	72,18	90,37
First phase of motion	Left Limb	77,54	82,95	80,33
	Right Limb	89,55	73,72	86,78
Second phase of motion	Left Limb	74,6	78,54	80,35
	Right Limb	95,6	72,97	85,61

left limb. For the third patient (p3) the results show a larger motor deficit in the left limb, but the ULMDI values are reduced for both limbs. These results in full extent reflect the actual state of the patient. In the cases of patients p1 and p3 motor dysfunction concerned the left limb for which, in both cases, a much lower value of the ULMDI index was obtained, whereas the patient p2 had motion problems in both limbs, what was also reflected in the calculated index.

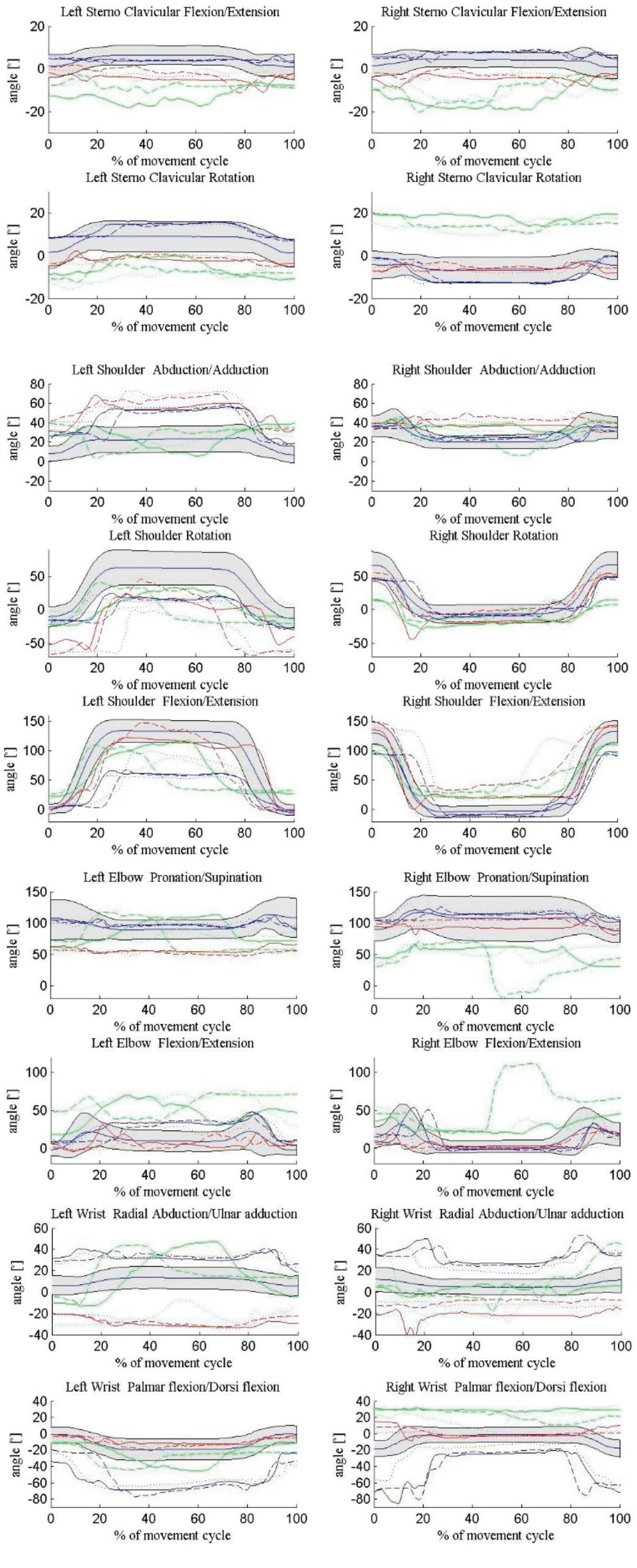

Fig. 4. The angular values of joints of the upper limb during performing of the sequence of movement by the tested patients – colors: red patient 1, green – patient 2, blue – patient 3, gray area: the normative results of control group

Additionally, in order to verify the correctness of performed calculations of ULMDI index kinematic waveforms of angles, based on which the index is calculated, were analyzed to indicate to what extent the existing changes in these waveforms were reflected in the in the value of index. Figure 4 shows three recorded changes of waveforms angles in the joints of patients together with the standard deviation obtained for the healthy persons. A detailed list of patients' waveforms deviating significantly from the model waveforms are summarized in Table 4.

For the patient p1 it was noted that the difference in angles' waveforms comparing to the measurement of healthy people occurred in all 3 waveforms in the right limb and 6 in the left limb. This resulted in a reduction of the ULMDI index to 90 in the right limb and 74 in the left one. In the case of patient 2 such differences were noted in 7 movements in both right and left limb. The value of ULMDI index was 72 for the right limb and 76 for the left one. In the case of the third patient there was the reduction of the index to 90 in the right limb caused by 2 waveforms which differed from the waveforms for healthy people, and to 76 in the left limb with 6 different waveforms. These results show that not only was the existing dysfunction reflected in the value of the index, but also the comparable index value was obtained for a similar level of the dysfunction. Similar relationships can be seen trough analyzing the different phases (Fig. 2) of the described sequence of motion (Fig. 4, Tab. 3).

4. Discussion

The literature research has shown that there are a lot of medical scales that describe the severity of the dysfunction of the human movement [16], [22], [23]. However, all these scales operate on the basis of the assessments made by the physician or patient. Much more objective assessment is provided by the indexes calculated on the basis of advanced mahematical and biomechanical measurements because they are based on the values measured using equipment specially designed for that purpose excluding the element of the subjective opinion about the level of medical condition and making such assessment comparable between

Table 4. The movements of the individual joints of the upper limbs of patients p1, p2 and p3, where it was discovered that for most of the time of performing the movement the angle waveforms do not fall within the normative results obtained by the control group. The particular symbols stand for: flexion/extension in sternoclavicular joint (*sc.fe*), rotation in the sternoclavicular joint (*sc.r*), abduction/adduction at the glenohumeral joint (*gh.aa*), rotation of the glenohumeral joint (*gh.r*), flexion/extension the glenohumeral joint (*gh.fe*), pronation/supination of the elbow joint (*e.ps*), flexion/extension the elbow (*e.fe*), elbow adduction/radial abduction of the wrist joint (*w.rdud*), palmar/dorsal flexion of the wrist joint (*w.fe*)

Subjects	Movements in individual joints of left limbs	The number of deviation of left limb	Movements in individual joints of right limbs	The number of deviation of right limb
p1	sc.fe, sc.r, gh.aa, gh.r, e.ps, w.rdud	6	gh.aa, gh.fe, w.rdud	3
p2	sc.fe, sc.r, gh.r, gh.fe, e.ps, e.fe, w.rdud	7	sc.fe, sc.r, gh.aa, gh.fe, e.ps, e.fe, w.fe	7
p3	gh.aa, gh.r, gh.fe, e.fe, w.rdud, w.fe	6	w.rdud, w.fe	2

those engaged in the research and between medical centers. Many such indexes have been developed for the lower extremities, in particular for gait analysis [2], [10], [20]–[22]. However, in the case of the upper extremities the possibility of such an analysis is limited to only a few indexes [4], [8], [16]. In addition, the algorithms for setting all the indexes for the upper extremities consist of the calculating the difference of root mean square (RMS) between the set of kinematic parameters of the tested person and the average values of parameters for a group of healthy people. However McMulkin and MacWilliams in their work [10], have analyzed the indexes used to evaluate gait and demonstrated that the most sensitive measure of assessment of the differences before and after treatment, and comparing the results with a control group, are indexes calculated on the basis of the algorithms comparing the images on which GDI is based. What is more, it is very important to properly select the input parameters taken into consideration in the calculation algorithm. One of three existing indexes is Arm Posture Score, predefined only for evaluation of upper limb during walking, which is constructed with the use of only 4 parameters determining the flexion and extension in the joints of the upper limb and adduction/abduction in the shoulder joint [16]. Butler and co-workers proposed PULMI index for evaluating the function of the upper limbs during movement of reaching and grasping. It is constructed on the basis of 8 kinematic waveforms values among which flexion/extension in the shoulder joint, and abduction/adduction at the same joint [4] are missing. The absence of these parameters, particularly as far as patients with motor deficits are concerned, can result in the evaluation using this index not being credible.

The objective of the research described in this work was to formulate a new index to assess the function of the upper limbs, which will be the first index dedicated to the upper limbs calculated on the basis of algorithms for image comparison [22]. In addition, the calculation of the ULMDI index has taken into account the waveforms of angles in the joints of the upper limb which were omitted in PULMI index, so it can be assumed that it will allow the assessment of dysfunction to be more reliable.

In addition, it is possible to predict of decreasing of ULMDI values on the basis of research presented in [7], [10], [15] for GDI index, which algorithm of setting is the same as used in the calculations for ULMDI. In these studies, the authors compared the indexes GGI, GDI, GPS/GDI in the population of people with typical gait pathologies (7 groups of patients who had different pathologies of gait and underwent surgical treatment). These studies showed that the indexes GGI and GDI ($GDI^* = 100 - 10x\left(\frac{\ln(GPS) - \text{mean}(\ln(RMS_{\text{control}}))}{SD(\ln(RMS_{\text{control}}))}\right)$ are the most intuitive measure of assessment of clinical lesions.

Calculation of ULMDI index is based on algorithms for image comparison which allows to set the numerical similarity of one image to the others taken as a reference. The course of change of the angle obtained for the patient is compared individually to each of the reference waveform (it is not the comparison to the mean standard). In order to facilitate the interpretation of the index in clinical practice, a number that specifies the similarity has been scaled to the average value of 100 (based on the similarities of all standard waveforms to each other), and the standard deviation to the value of 10. This approach has been proposed by Schwartz [22].

Making the assumption above, if among the standard waveforms there are waveforms similar to the analyzed ones the value of the ULMDI index will not differ significantly from the value of 100. However, if the patient's outcome is different from any of the standard waveforms, the value of the index will decline (the greater the differences in the image of analyzed waveforms, the smaller value of the index).

Determining the ULMDI index in the way proposed in this paper, the similarity of waveforms of nine values of specified kinematic values in the joints of the upper limb of the diagnosed person in relation to the same kinematic value collected for all waveforms taken as a reference (obtained by a healthy person performing the moves analogous to those performed by the patient) is defined.

It has been shown that the developed ULMDI index allows to detect the deviations in the performance of movements from the accepted norm. The results showed that both the description of the motor dysfunction of examined person based on the diagnosis of the physician, a detailed analysis of kinematic waveforms received during the tests and the calculated values provide a coherent picture of the state of a human movement. The index analysis is for the doctor less time-consuming, and the comparison of the results at various stages of therapy gives an objective picture of the progress that the patient has made.

5. Summary

The research led to the development of a new index allowing for an assessment of the severity of the dysfunction of the musculoskeletal system of the upper limb on the basis of kinematic waveforms. The proposed index uses waveforms of angles in various joints of the upper limb as an input. The calculation of the index is based on the method of comparing images referring the analyzed waveforms to the waveforms treated as a reference. The index value indicates how much the execution of a given movement differs from the norm. Such an examination done by a physician or physiotherapist for selected movement sequences will give a complete picture of the serious condition of the existing motor dysfunction. Proposed ULMDI index can be used to analyze any movement sequences performed by the upper limb. To do this, however, in the first place one has to carry out the measurements of healthy people in order to gather the base model waveforms.

Further work related to the use of ULMDI index in clinical practice should refer to selection of such movement sequences, which would allow for an objective assessment of the existing motor dysfunction of the patient and for the use in the assessment of the rehabilitation process.

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