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Motor functions assessment method based on energy changes in gait cycle

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Purpose: The aim of the research was to determine the energy changes during the gait cycle for a group of healthy children and a group of patients with cerebral palsy, and to compare the value of energy expenditure (*EE*) with the determined values of the Gillette Gait Index (*GGI*) and the Gait Deviation Index (*GDI*).

Methods: The study group consisted of 56 children with regular gait and 56 patients with diagnosed cerebral palsy (*CP*). The gait kinematics was determined by BTS Smart System. Based on the identified position of the body mass, the following parameters were determined: the potential energy, kinetic energy, and total energy. The values were standardized to 100% of the gait cycle. The values of the Gillette Gait Index (*GGI*) and the Gait Deviation Index (*GDI*) were calculated using the authors' own software.

Results: Values of potential, kinematic and mechanical energy changes and mean values of total energy (energy expenditure – *EE*) were calculated for a reference group and for patients with *CP*. The obtained results were standardized in relation to the body mass and stride length. Furthermore, the values of the Gillette Gait Index (*GGI*) and the Gait Deviation Index (*GDI*) were calculated. Statistical analysis of the obtained results was performed. The Spearman rank correlation coefficient was defined between the calculated GGI and GDI values and energy expenditure EE.

Conclusions: Values of energy expenditure changes can be used as an objective comparative tool for gait results concerning children with various neurological and orthopaedic dysfunctions.

Key words: *cerebral palsy, energy expenditure, gait indices*

1. Introduction

Gait analysis has been more and more often used as a diagnostic method of the motor organ in both scientific research and clinical application. Accessibility of Motion Capture systems enabled many hospitals and other health care units to use gait analysis as a part of their diagnostic process, selection of adequate methods of treatment as well as verification of the achieved results of the motor organ rehabilitation [1], [13], [14]. Some scientists believe that only using this type of tests the correct diagnosis and selection of proper methods of treatment is possible [11], [14]–[16], [21].

The history of gait research is closely connected with the development of image recording methods which go back to the late 19th century. The pioneer in this field is Ètienne-Jules Marey, who examined motor functions using a self-developed method based on chronography. At the same time, other scientists, such as Braun and Fischer, researched gait and using the footage recorded by several video cameras developed a method which enabled a three-dimensional analysis of movement [1]. In the early 1950s, Saunders et al. [16] presented concepts of the assessment of motor functions and diagnostics of patients by means of six determinants of gait. The method was based on an assumption that all gait pathologies cause the increase of energy expenditure and the defined determinants

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are closely related to such expenditure. The late 20th century witnessed a rapid development in the research related to the functional evaluation of patients with the use of Motion Capture systems. It resulted, among other things, in the standardization of testing methodology as well as the development of commercial systems of motion analysis. Moreover, it enabled the determination of standard values for time-spatial, kinematic and dynamic parameters of gait, which constitute the basis for the assessment of patients with motor organ disorders [10], [15], [19], [20]. Apart from unquestionable advantages, the use of gait analysis in practical application is not free from drawbacks. The amount of data obtained in such analysis is huge (angles in joints, moments in joints). Also, to draw conclusions concerning the selection of treatment methods, experience in the interpretation of measurement data is required. Index methods allow for some facilitation of the interpretation of results obtained from the research of gait kinematics. Calculation of such indices enables the description of the patient's gait by means of a single dimensionless number which shows how it diverges from the average value of regular gait [1], [14], [19], [20]. The most known as well as more and more frequently used indices are: Gillette Gait Index (*GGI*) and Gait Deviation Index (*GDI*). The Gillette Gait Index, which was developed by Schutte et al. [19], determines the degree of gait normality. The *GGI* uses the Principal Component Analysis (*PCA*) method of determination in order to obtain 16 independent variables for the selected gait parameters. The Gait Deviation Index (*GDI*), which was developed by Schwartz and Rozumalski in 2008, is defined as an index of gait deviation. In order to calculate the *GDI*, a set of 9 input variables defining the kinematics of the motion of pelvis, the hip, knee and tarsal joints should be taken into account [20]. A wide application of gait kinematics analysis is, however, hindered by the purchasing costs of the measurement systems as well as the necessity of having a large area in order to correctly conduct the tests.

The data obtained from the measurements of gait kinematics may also serve the purpose of the analysis of the change of energy expenditure during gait. The determination of energy expenditure, which should be understood as motion efficiency, is an important study complementing the research on motor functions. The use of energy may be divided into two types. The first one is connected with the Basal Metabolic Rate (*BMR*), whereas the second one with the performance of various activities, such as physical activity or intellectual activity [21]. One of the evaluation methods of energy expenditure during a given physical activity consists in the measurement of the use of oxygen during effort [21]. However, due to the fact that the application of Douglas bags collecting the exhaled air proved to be troublesome and uncomfortable in the case of children, simpler and cheaper methods were searched for to be used in energy expenditure assessment [2], [8]. In order to evaluate energy expenditure, researchers commonly started to use indices based on the pulse measurement: *EEI* (Energy Expenditure Index), known also as *PCI* (Physiological Cost Index) as well as *TCI* (Total Cost Index) [8]. The EEI (*PCI*) is quite commonly used in the evaluation of energy expenditure during gait in patients with cerebral palsy after medical interventions (such as surgical or pharmacological treatment) as well as in the assessment of effect of rehabilitation [8]. Also, the evidence of a strong and significant correlation between the metabolic cost and the applied medical scale, namely the Gross Motor Function Classification System, was shown.

The use of mechanical energy during locomotion can be determined as the sum of potential and kinetic energy of the centre of gravity of a body, and the sum of kinetic energy of the body segments in the progressive and rotational motion in relation to the centre of gravity of the body. Cavagna showed in his research [1], [3] that during gait there is a change of potential energy into kinetic energy and vice versa, however, such changes are not total. At optimum gait velocity, the maximum value of kinetic energy occurs when potential energy reaches its minimum value and the other way round. However, along with the increase of gait velocity, a shift in the phase occurs. Cavagna divided the total mechanical work during gait into external work and internal work. The former is necessary for the displacement of the gravity centre in space while the latter for the displacement of body segments in relation to the gravity centre [1], [3]. Moreover, the mechanical work of muscles during gait may be considered as positive or negative work. The muscles which transmit energy to the limbs in concentric contractions do positive work when the force moment generated by them as well as angular velocity in the joint axis have the same sense. However, during eccentric contractions of the muscles when the force moment and the angular velocity have opposite senses, the muscles absorb the energy and thus do negative mechanical work [5].

Appropriate coordination of individual segments of the body enables the correct conversion between potential and kinetic energy. Moreover, it enables the maintenance of a steady level of energy in the gait cycle, that is the sum of potential and kinetic energy of the whole body. Disturbed motor coordination, for instance in patients with hemiparesis, causes desynchronization of the changes of kinetic and potential energy of the centre of the body mass. This fact results in the appearance of compensation mechanisms causing the reduction of energy use which had been increased due to functional disorders [21].

Numerous publications [3]–[6], [21], [24], [25] concentrated on the determination of potential and kinetic energy generated during gait and run. Wiliams and Cavanagh built models enabling the calculation of energy expenditure during gait using of three subsequent methods: first, calculating of mechanical energy solely for the gravity centre of the body; second, taking into consideration kinetic energy of the motion of body segments in relation to the centre of gravity; third, modelling of the energy losses and energy storage in elastic elements as well as of the energy flow between the segments of the body [24]. The purpose of Van de Walle et al.'s research [23] was to assess the expenditure of metabolic and mechanical energy during gait in 5 age groups of healthy participants ranging from 3 to 35 years of age. Dziuba et al. in their work [7] designed a method of the calculation of unit mechanical work during gait at different velocity in children with cerebral palsy. The researchers also determined the dependency of such work on motion velocity. Additionally, the authors proposed I_{seg} index which enables finding differences in the work done by particular limbs in patients suffering from motor function disorders. This index defines the relation of the total work done by the segments of lower limbs during gait of a given patient, expressed as a relation of a percentage of the total work in the gait cycle to the work done by the body segments of healthy people [7]. Another research, conducted by Chwała et al. [4], [5], examined the changes of potential, kinetic and total energy of the gravity centre of the body during physiological and sport gait. Tests performed by Khodadaeh [10] on patients before surgical procedures and after the implantation of endoprostheses confirmed that the relation of kinetic energy to potential energy in the gait cycle may support the assessment of motion pathology in patients.

In spite of numerous research papers dedicated to the determination of potential, kinetic and total energy during gait as well as the calculation of the energy recovery coefficient, the authors of this paper have not found any information concerning an attempt of correlation of the above-mentioned parameters with the results of the *GGI* and the *GDI*, which have been more and more often used in health care institutions and gait analysis laboratories. Also, the analysis of the existing literature did not reveal any significant research papers which would determine the values of the changes of potential and kinetic energy in relation to the transverse axis, sagittal axis as well as vertical axis of the body in patients with cerebral palsy.

Taking the above into consideration, the researchers decided to determine in this paper the changes of mechanical and potential energy as well as the components of kinetic energy for a group of healthy children and a group of patients with cerebral palsy. The ultimate goal of this work was to provide the assessment of the diagnostics of patients based on the energy changes during the gait cycle comparing the value of energy expenditure (*EE*) with the determined values of the Gillette Gait Index (*GGI*) and the Gait Deviation Index (*GDI*).

Table 1. Characteristics of patients with CP and reference subjects

	Summary statistics	Reference	*CP*	*CP-BTX*
Number (Men/Woman)		56 (28/28)	56 (35/21)	16 (9/7)
Age [years]	mean (SD)	11 (3)	8 (4)	5 (3)
Body height [m]	mean (SD)	1.47 (0.17)	1.26 (0,23)	1.14 (0.16)
Body mass [kg]	mean (SD)	44 (14)	28 (13)	22 (8)
BMI [kg/m^2]	mean (SD)	19 (3)	16 (3)	16 (3)

Table 2. Characteristics of patients with cerebral palsy

	Summary statistics	Hemiplegia	Diplegia	Quadriplegia
CP	Percent (number of patients)	25% (14)	61% (34)	14% (8)
CP-BTX		31% (5)	56% (9)	13% (2)

2. Materials and methods

The study group consisted of 56 children with regular gait (Group 1 – Reference) and 56 patients with diagnosed cerebral palsy (Group 2 – *CP*). All the patients with *CP* were subjected to individually matched rehabilitation, moreover, 43 patients were qualified for the treatment utilizing botulinum toxin of type A. In the group of patients with *CP*, 16 people were selected. Their motor functions had been tested before the treatment and then 6 months after the administration of botulinum toxin (Group 3 = *CP-BTX*). The detailed characteristics of the study groups have been presented in Tables 1 and 2.

The study group consisted of 56 children with regular gait and 56 patients with diagnosed cerebral palsy (*CP*). Patients for the tests were qualified by doctors. During the selection of patients to the test group, the following criteria were applied:

- age from 30 months to 18 years old;
- diagnosed cerebral palsy in the form of spastic hemiplegia or double hemiplegia (diagnosis on the basis of clinical picture and neuro-imaging test results);
- patients treated with botulinum toxin and rehabilitated;
- patients qualified to at least 2nd level on GMFCS scale;
- parents' consent to conduct the gait tests;
- patients who walk unaided and who cooperate.

The experimental tests of gait were performed in the Upper Silesian Child Health Centre in Katowice. In order to carry out the tests, a positive expert opinion was obtained from the Bioethical Commission of the Medical University of Silesia in Katowice. Gait kinematics was recorded utilizing a system for a three-planar analysis of motion called BTS Smart. It consists of a set of 8 video cameras recording the changes of markers' location, 2 vision cameras, and 2 Kistler dynamometric platforms. According to the adopted Davis model, reflective markers were placed in precisely defined anatomical points on the patient's body. During the measurement process the markers were recorded by the system of video cameras. Each test consisted of two fundamental stages: a static examination and a dynamic examination (of gait) during which patients had to walk barefoot on the measurement walking path at their natural walking speed. Using a device for the system calibration, the measurement path was connected with the system of coordinates defining the directions of motion. The beginning of the system of coordinates was connected to one of the dynamometric platforms placed in the gait path. The orientation of the system of coordinates defined the motion along *X*-axis as the motion of the gravity centre of the body on the transverse axis (motion in the right and left direction), the motion on *Z*-axis as the motion in the direction of the sagittal axis and the motion along vertical *Y*-axis as the up-and-down motion.

Time and spatial parameters as well as gait kinematic parameters were determined for all the tested participants. Using the authors' applications, the values of the Gillette Gait Index (*GGI*) and the Gait Deviation Index (*GDI*) were calculated. The values of the indices were determined separately for the right and left lower limb.

Applying a kinematic method that utilizes the location of the gravity centre of the body, the researchers determined the mechanical work during gait.

For each examined person, the researchers determined instantaneous values of potential energy, resultant kinetic energy and its components as well as total energy standardized to 100% of the gait cycle. The instantaneous values of all components of energy were standardized in relation to the body mass.

Next, mean values of the changes of potential energy in the whole cycle were calculated and standardized in relation to the body mass and to the stride length of the tested person:

$$\Delta E_{p_{\text{stand}}} = \frac{m_c g(h_{\max} - h_{\min})}{m_c sl} \quad [\text{J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}] \qquad (1)$$

where:

$\Delta E_{p_{\text{stand}}}$ – mean value of potential energy changes during gait standardized in relation to body mass and the distance traveled $[\text{J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}]$,

g – earth gravitational acceleration,

$h_{\max}$, $h_{\min}$ – the highest and the lowest location of the centre of mass CoM, respectively, in the gait cycle [m],

m_c – body mass of the person tested [kg],

sl – stride length of the person tested [m].

Then, the mean value of the changes of resultant kinetic energy was determined in a single gait cycle, which was also standardized in relation to the body mass and the distance traveled:

$$\Delta E_{k_{\text{stand}}} = \frac{m_c (\Delta V_w)^2}{2 m_c sl} \quad [\text{J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}] \qquad (2)$$

where:

$\Delta E_{k_{\text{stand}}}$ – mean value of the changes of resultant kinetic energy standardized in relation to the body mass and the distance traveled $[\text{J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}]$,

ΔV_w – change of resultant velocity of the centre of the body mass $[\text{m}\cdot\text{s}^{-1}]$,

m_c – body mass of the person tested [kg],

sl – stride length of the person tested [m].

The mean value of the total energy changes of the body in the gait cycle, which was standardized in relation to the body mass and the distance traveled, was defined as the sum of the mean value of changes of potential energy and resultant kinetic energy of the centre of the body mass:

$$\Delta E_{c_{\text{stand}}} = \Delta E_{p_{\text{stand}}} + \Delta E_{k_{\text{stand}}} \quad [\text{J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}], \qquad (3)$$

The mean value of the total energy changes of the body in the gait cycle was defined as energy expenditure and marked with symbol *EE*:

$$EE = \Delta E_{c_{\text{stand}}}. \qquad (4)$$

The obtained measurement data was subjected to a detailed statistical analysis. Using the Shapiro–Wilk test, the regularity of the distribution of all the analyzed variables was checked. Then, the basic descriptive statistics was developed for them by means of determining the respective mean values, standard deviations, the median as well as minimum and maximum values in all study groups. The next step involved performing statistical tests adequate for independent tests (the Mann–Whitney *U* test and Student's *t*-distribution) in order to find out whether there are any significant statistical differences between the obtained values of the *GGI*, *GDI* and *EE* for the control group (standard) and the patients with cerebral palsy. The Spearman rank correlation coefficient was defined between the calculated *GGI* and *GDI* values and energy expenditure *EE*. Moreover, the nonparametric Wilcoxon test was applied to check whether the differences between the determined *GGI*, *GDI* and *EE* in an initial test and in the test conducted 6 months after botulinum toxin administration in group 3 (patients with *CP*) had any statistical significance.

3. Results

Figure 1 presents the obtained diagrams of the instantaneous value of potential energy, resultant kinetic energy and total energy, standardized in relation to

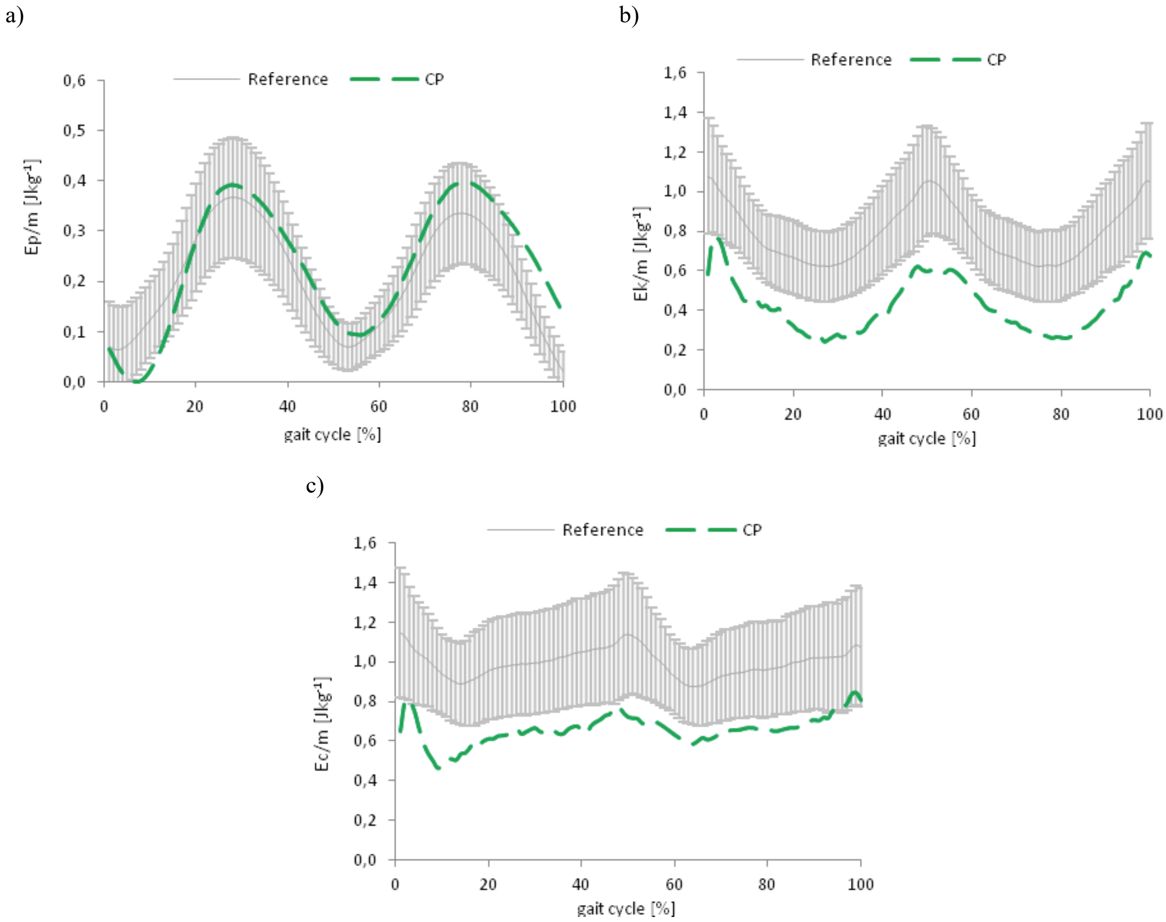

Fig. 1. Instantaneous values of potential energy (a), resultant kinetic energy (b) and total energy (c) standardized in relation to body mass for the group of children with regular gait and a selected patient with cerebral palsy

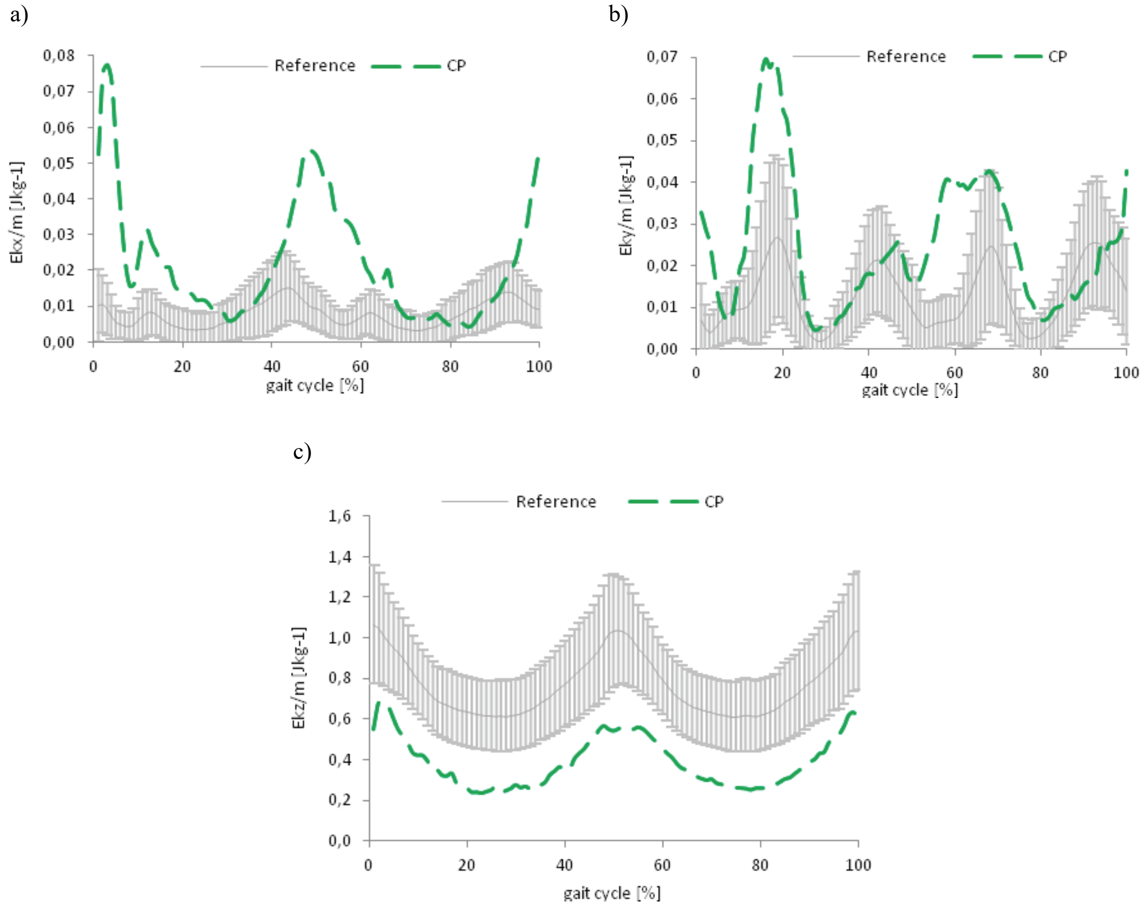

Fig. 2. Instantaneous values of kinetic energy in relation to the transverse axis (a), vertical axis (b) and sagittal axis (c) of the body standardized in relation to body mass for the group of children with regular gait and a selected patient with cerebral palsy

Table 3. Mean, minimum and maximum values, and the median of the changes of potential energy, resultant kinetic energy and total energy of the gravity centre in the gait cycle, standardized in relation to body mass and a distance traveled for the group of children with regular gait and patients with cerebral palsy

	Summary statistics	$\Delta E_{p_{stand}}$ [$Jkg^{-1}m^{-1}$]	$\Delta E_{k_{stand}}$ [$Jkg^{-1}m^{-1}$]	$\Delta E_{c_{stand}}$ [$Jkg^{-1}m^{-1}$]
Reference	mean ± SD	0.37 ± 0.07	0.13 ± 0.07	0.50 ± 0.11
	median	0.36	0.11	0.48
	min÷max	0.21÷0.53	0.06÷0.5	0.29÷0.88
CP	mean ± SD	0.56 ± 0.23	0.23 ± 0.12	0.8 ± 0.3
	median	0.48	0.21	0.73
	min÷max	0.26÷1.31	0.06÷0.55	0.37÷1.73

Table 4. Mean values of total energy of the gravity centre in the gait cycle, standardized in relation to body mass and the distance traveled for the group of children with regular gait, presented in 3 age groups

Age [years]	Number of subjects	*EE* [$Jkg^{-1}m^{-1}$] (mean ± SD)
6–9	16	0.47 ± 0.08
10–13	26	0.54 ± 0.12
14–17	14	0.44 ± 0.09

body mass for the group of children with regular gait and for a selected patient with cerebral palsy. Figure 2 demonstrates instantaneous values of kinetic energy in relation to the transverse, vertical and sagittal axes of the body, standardized in relation to body mass for the control group and a patient with *CP* (the broken green line).

Table 3 presents mean values, minimum and maximum values, and the median of the standardized changes of potential, kinetic and total energy per kilogram of body mass and a metre of the distance traveled in the group of children with regular gait and patients with cerebral palsy.

Mean values of total energy (energy expenditure – *EE*) obtained for healthy participants have been presented in three age groups: 6–9, 10–3 and 14–17 years of age (Table 4).

Within the framework of this research, instantaneous values of velocity components were also determined. On their basis, mean values of the changes of kinetic energy were determined in relation to the transverse axis (ΔE_{kx}), sagittal axis (ΔE_{kz}) and vertical axis (ΔE_{ky}) of the body in the gait cycle. They were standardized in relation to body mass and the distance traveled for the control group and patients with cerebral palsy, which is presented in Table 5.

Table 6 compares the obtained values of the gait indices, such as Gillette Gait Index and Gait Deviation Index as well as energy expenditure *EE* for the group of healthy children and patients with cerebral palsy. The comparison of the results obtained for individual study groups are also presented in a graphic way (Fig. 3).

Table 5. Mean, minimum and maximum values as well as the median of the component changes of kinetic energy of the gravity centre in the gait cycle, standardized in relation to body mass and the distance traveled for the group of children with regular gait and patients with cerebral palsy

	Summary statistics	$\Delta E_{kx_{\text{stand}}}$ [Jkg^{-1}m^{-1}]	$\Delta E_{ky_{\text{stand}}}$ [Jkg^{-1}m^{-1}]	$\Delta E_{kz_{\text{stand}}}$ [Jkg^{-1}m^{-1}]
Reference	mean ± SD	0.0196 ± 0.0076	0.0298 ± 0.0155	0.4667 ± 0.1409
	median	0.0179	0.026	0.456
	min÷max	0.0063÷0.0381	0.0089÷0.0760	0.2709÷1.0073
CP	mean ± SD	0.0582 ± 0.0681	0.0351 ± 0.0239	0.3655 ± 0.2062
	median	0.0374	0.0292	0.35
	min÷max	0.0111÷0.3878	0.0065÷0.1057	0.0411÷1.1315

Table 6. Mean, minimum and maximum values as well as the median of the *GGI* and *GDI* as well as energy expenditure (*EE*) for the group of children with regular gait and patients with cerebral palsy

	Summary statistics	Reference	*CP*
GGI	mean ± SD	15.71 ± 5.56	292.17 ± 313.12
	median	16.23	163.26
	min÷max	6.70÷29.16	27.18÷1477.00
GDI	mean ± SD	99.23 ± 8.45	76.76 ± 10.87
	median	100.29	77.14
	min÷max	78.95÷121.07	52.97÷101.72
EE [Jkg^{-1}m^{-1}]	mean ± SD	0.50 ± 0.11	0.8 ± 0.3
	median	0.48	0.73
	min÷max	0.29÷0.88	0.37÷1.73

Table 7. Values of the Shapiro–Wilk test for the *GGI* and *GDI* as well as energy expenditure (*EE*) obtained for the control group and patients with cerebral palsy

	GGI		*GDI*		*EE*	
	Reference	*CP*	Reference	*CP*	Reference	*CP*
Shapiro–Wilk test (p)	0.02	0.00	0.35	0.38	0.04	0.00

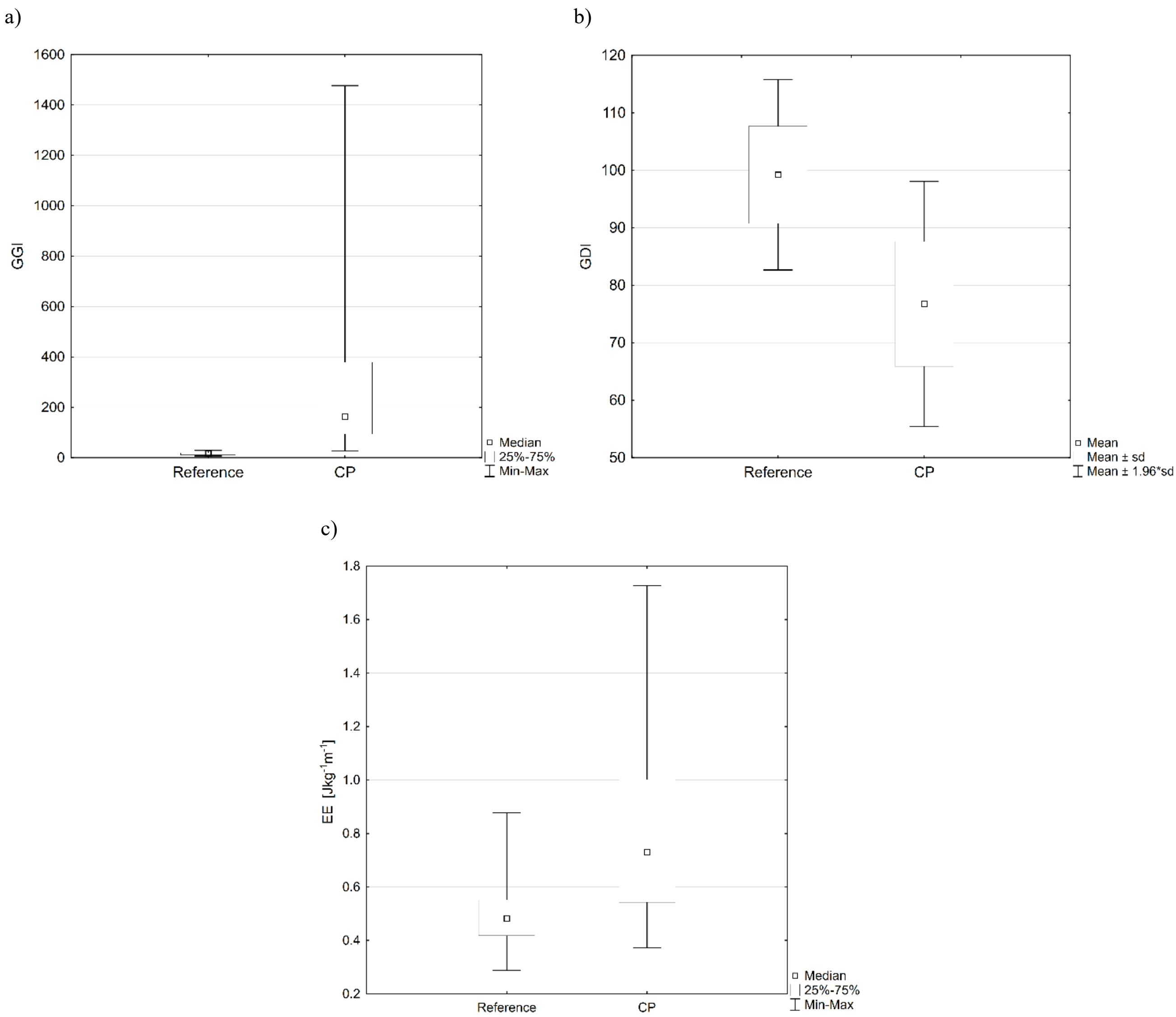

Fig. 3. Results of indices: a) *GGI*, b) *GDI*, c) EE for the control group and patients with cerebral palsy

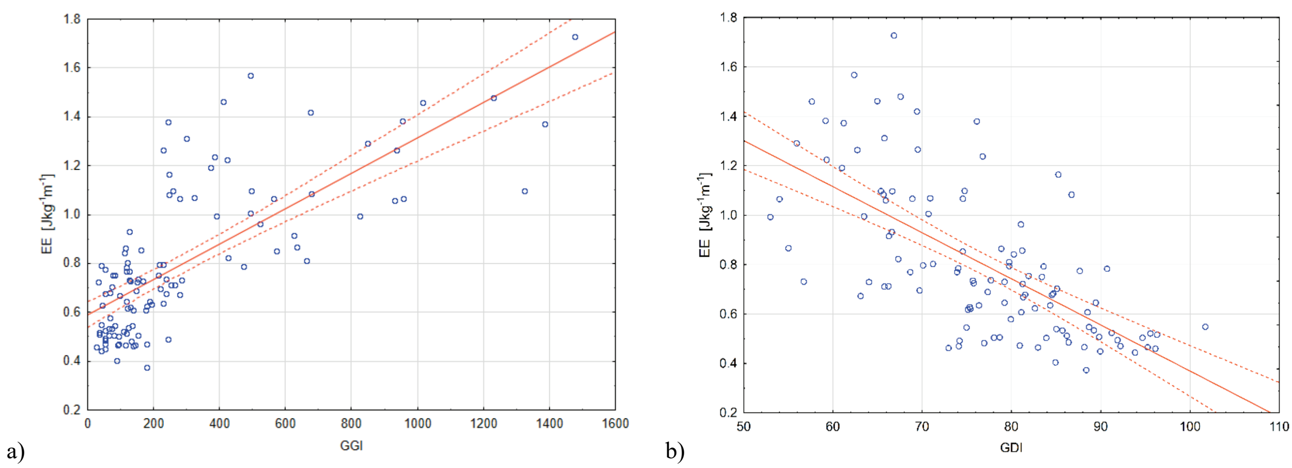

Fig. 4. Diagram of dispersion between: a) *GGI* and *EE* values,
b) *GDI* and *EE* values obtained for participants with cerebral palsy

Table 8. Mean, minimum and maximum values as well as the median of the indices *GGI*, *GDI* and energy expenditure (*EE*) values for patients with cerebral palsy appointed in the initial examination (*IE*) and 6 months after botulinum toxin administration (B6m)

		IE	B6m
GGI	mean ± SD	293.23 ± 258.20	256.53 ± 301.09
	median	201.53	127.74
	min÷max	78.12÷1017	33.54÷1227.9
GDI	mean ± SD	74.52 ± 8.55	77.35 ± 11.58
	median	75.44	78.17
	min÷max	57.64÷88.52	52.84÷96.30
EE [$Jkg^{-1}m^{-1}$]	mean ± SD	0.90 ± 0.35	0.90÷0.43
	median	0.80	0.76
	min÷max	0.40÷1.57	0.50÷2.72

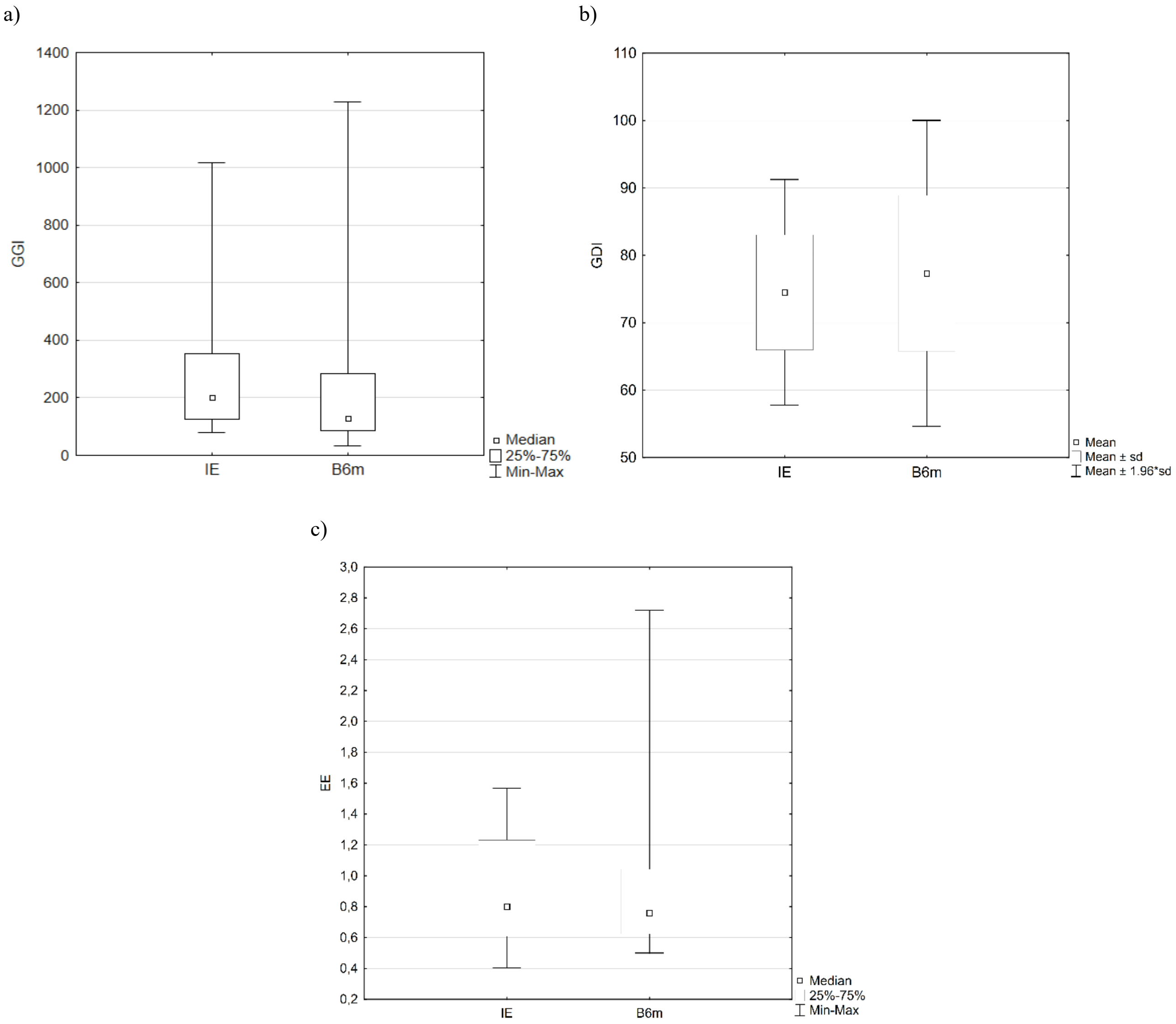

Fig. 5. Results of: a) *GGI*, b) *GDI* and c) energy expenditure (*EE*) for the group of children with regular gait and patients with cerebral palsy appointed in the initial examination (*IE*) and 6 months after botulinum toxin administration (B6m)

The researchers checked regularity of the obtained values of the *GGI* and *GDI* as well as the value of the calculated energy expenditure *EE*, which were standardized in relation to body mass and stride length for the group of patients with regular gait and the group of 56 patients with cerebral palsy. Based on the Shapiro–Wilk test, the regularity of the results distribution of the Gait Deviation Index was demonstrated while, with the adopted significance level of 0.05, no regularity of distribution was shown for the *GGI* and *EE* (Table 7).

Within the framework of this research, the obtained results of the *GGI*, *GDI* and *EE* for the control group (the standard) and patients with cerebral palsy were checked for the occurence of any statistically significant differences between the two groups. In order to verify this, the Mann–Whitney U test and Student's *t* test for independent tests were conducted (depending on the distribution regularity of a particular variable). All analyzed parameters significantly differed between groups, with the adopted significance level of $\alpha = 0.05$.

The Spearman rank correlation coefficient was defined between the values of the Gillette Gait Index, the Gait Deviation Index, and energy expenditure EE calculated for patients with cerebral palsy. Between the *GGI* and *EE* values, a positive correlation of 0.74 was obtained, whereas between the calculated *GDI* and *EE*, a negative correlation of –0.68 was obtained. The calculated correlation indices are statistically significant. Figure 4 presents diagrams of dispersion of the analyzed variables.

Table 8 juxtaposes the values of gait indices: the *GGI*, the *GDI* and energy expenditure *EE* for 16 patients with cerebral palsy (group III – CP-BTX) appointed in the initial examination (*IE*) and 6 months after botulinum toxin administration (B6m). The comparison of the results obtained before the treatment as well as 6 months after the injection of botulinum toxin and rehabilitation has been demonstrated in Figure 5.

It was proven, based on the nonparametric Wilcoxon test, that the differences between the GGI and GDI results obtained in the initial examination and in the examination conducted 6 months after botulinum toxin administration are statistically significant ($p \leq 0.05$). No statistically significant differences were found between the results of the calculated energy index ($p = 0.75$).

4. Discussion

In the hitherto research authors have often undertaken the determination of energy expenditure during gait in various test groups. Studies refer to the assessment of energy balance in children and adults, including the elderly [6], [18]. There is also well-known research concerning the evaluation of mechanical energy in patients with motor system dysfunctions. The research proved that the applied procedures of the calculation of mechanical work are sufficiently sensitive to identify differences between pathological gait and the gait of healthy individuals [2], [3], [21].

The methodology proposed in this work enabled the determination of momentary changes in the values of potential energy, resultant kinetic energy and its components as well as total energy for a group of healthy children who may constitute the standard ranges. The obtained courses of momentary changes of particular components of energy correspond to their counterparts described in literature [5], [6], [21]. The standard courses of changes of individual energy components during gait may be helpful in the diagnosing process of patients with motor system disorders.

The average level of changes of total energy ΔE_c in relation to the group of healthy children in the author's own research was restricted within the range of 0.29÷0.88 [$Jkg^{-1}m^{-1}$]. The mean value related to the control group amounted to 0.50 [$Jkg^{-1}m^{-1}$] and was by approximately 0.1 [$Jkg^{-1}m^{-1}$] higher than the mean value obtained in relation to a similar age group referred to in the work by Van de Walle et al. [21], demonstrating that the total value of energy expenditure during gait decreased along with age. The level of changes in the total energy in the research carried out by Chwała et al. [4], [5] in relation to the group of healthy adults walking with preferred natural velocity (restricted within the range of 1÷2 ms^{-1}) amounted to 0.36 [$Jkg^{-1}m^{-1}$]. The range of changes in the total energy during gait identified in the own research could be regarded as normative in relation to children aged 6–17. The lowest mean value of the total energy change was obtained in the group of the oldest children aged 14–17, whereas the highest value was revealed from the largest group of examined children aged 10–13 (Table 4).

In the author's research the mean value of the total energy changes in relation to the group of 56 patients with cerebral palsy amounted to 0.8 [$Jkg^{-1}m^{-1}$], which constituted 160% of the mean value obtained in relation to the control group. The values of ΔE_c in relation to the patients with CP are restricted within the range of 0.37÷1.73 [$Jkg^{-1}m^{-1}$]. The maximum value of ΔE_c was more than twice higher than the maximum value concerning the group of patients with regular gait. When testing children suffering from hemiplegia, Van den Hecke et al. obtained the total energy values higher by approximately 170% than when compared to those characterising the group of the healthy children [22]. Higher values of the total energy in patients with cerebral palsy were also obtained in the research performed by Dziuba et al. [6]. However, due to a different way of the standardisation of the results, their quantitative comparison is not possible.

The mean value of the changes in potential energy in the gait cycle in patients with cerebral palsy constituted 150% of the value obtained in relation to the control group (Table 3). When analysing the momentary changes in potential energy it was observed that a characteristic feature of the patients with cerebral palsy was a decrease in potential energy at the beginning of the gait cycle (during the loading response time), whereas at the same time the group of healthy individuals demonstrated a short period of energy stability followed by a rapid increase in energy until reaching the first local maximum (Fig. 1a). At the beginning of the stance phase, children with regular gait transfer their centre of gravity forwards and upwards. When analysing the gait of children suffering from cerebral palsy, it could be observed that the centre of gravity fell during the loading response phase. In addition, the gait cycle of patients with *CP* frequently began with the contact of the forefoot with the ground usually with excessively bent knee joints and ankles (and not the heel as is the case of healthy individuals). In the test group of patients with cerebral palsy, the value of potential energy constituted on average 70% of the total mechanical energy, whereas among healthy persons it amounted to 75%. In view of the foregoing, it could be concluded that the gait of children with *CP* was characterised by a 5% higher content of kinetic energy.

The mean value of the change in resultant kinetic energy in a single gait cycle was nearly twice higher in patients with cerebral palsy than in the group of healthy children (Table 3). When assessing the changes in kinetic energy during gait, the analysis of kinetic energy constituents was of particularly important, i.e., mean values of changes in kinetic energy in relation to the transverse (ΔE_{kx}), sagittal (ΔE_{kz}) and vertical (ΔE_{ky}) axis of the body. The above-mentioned quantities, standardised in relation to the body mass and the distance traveled during the tests, in relation to the control group and the group of the patients with *CP* are confronted in Table 5. The children with cerebral palsy revealed nearly twice higher mean value of changes in kinetic energy in relation to transverse axis ΔE_{kx}. Moreover, it was observed that the proportion of the mean velocity in the transverse axis (V_x) to the mean resultant velocity (V_w) in the group of patients with *CP* was more than 4 times higher than that obtained in relation to the patients with regular gait. A significantly higher value of constituent ΔE_{kx} in patients with *CP* could be ascribed to the excessive range of pelvic movements in the transverse plane (excessive rotation), being a characteristic of this condition and resulting from the reduced range of movement in the sagittal plane. The test group of the patients with cerebral palsy revealed the value of the mean change in kinetic energy in the sagittal plane (ΔE_{kz}) nearly by 20% lower in relation to the mean value concerning the healthy persons. The changes in kinetic energy in the vertical axis of the body (ΔE_{ky}) were by approximately 20% higher for the patients with *CP* compared to the results obtained for the standard.

The Mann–Whitney *U* test and the Student's *t*-test revealed that the differences between the values of the *GGI*, *GDI* and *EE* calculated in relation to the control group and to the patients with cerebral palsy were statistically relevant.

The superior objective of the research work was to determine the usability of the determination of the value of energy expenditure (*EE*) in the process of patient diagnostics. Therefore, it was necessary to investigate the correlations between the values of Gillette Gait Index (*GGI*), Gait Deviation Index (*GDI*), and the values of energy expenditure (*EE*) calculated in relation to the patients with cerebral palsy. Because of the lack of normality in relation to the distribution of variables subjected to analysis (*GGI* and *EE*), the coefficient of Spearman's rank-order correlation was calculated. Between the values of the *GGI* and *EE*, a positive correlation of 0.74 was obtained, whereas between the values of the *GDI* and *EE*, a negative correlation of –0.68 was obtained. The obtained correlation values indicated the existence of a relatively strong statistically relevant dependence. Therefore, it could be concluded that the *EE* index specifying the mean value of changes in the total energy of the body during a gait cycle could be a useful tool in diagnostic processes. The use of an accelerometer located on the pelvis and the calculation of energy expenditure could constitute a cheaper alternative to expensive optical systems used in the triplanar analysis of motion. In addition, the manner enabling the obtainment of necessary results presented above could be significantly simpler and faster.

The research work also involved the verification of differences between the results of the *GGI*, *GDI* and *EE* in relation to the group of 16 patients with *CP* (group III – *CP-BTX*) identified in the initial tests (*IT*) and in the test performed 6 months after the administration of botulinum toxin (B6m). The Wicoxon non-parametric test conducted within the research revealed the existence of statistically relevant differences in relation to the results concerning the *GGI* and *GDI*, whereas it did not reveal the existence of significant differences concerning the energy index values. However, it should be noted that the dependence was identified for a small group of 16 participants. In addition, half of the patients from group III were children below 6 years of age and, as rightly pointed out by Schepens et al. [18], energy expenditure-related results (value of work performed internally and externally) in relation to younger children (below six years of age) should be treated with extra care, as they might not have fully developed the neurological mechanisms of gait. Therefore, to objectively assess whether an index concerning energy expenditure (calculated for the body's centre of gravity) could be used to measure progress in applied treatment, it would be recommended to identify the values of the *GGI*, *GDI* and EE in the initial test and in the post-treatment test in relation to a larger test group. Cate et al. [2] investigated changes in mechanical energy during the gait of persons after strokes and following the administration of botulinum toxin. The authors did not report any statistically relevant differences in total mechanical work, yet, they noted a decrease in oxygen consumption in the patients subjected to tests. In addition, as rightly indicated by Chwała W. [5], the mean values of variables might not demonstrate statistically relevant differences in the entire cycle of gait, yet they may vary in individual time intervals. The divergences in the time intervals could significantly affect the assessment of patients' motion. For this reason, the authors emphasize the necessity of further research related to the analysis of the similarity of courses of individual constituents of energy expenditure in the patients with *CP* and those of the control group as well as the comparison of courses in relation to various stages of treatment. The foregoing will enable an objective determination whether the course of standardised momentary values of variables are similar or whether they differ from one another in individual phases of gait.

5. Conclusions

1. The research work resulted in the identification of changes in mechanical and potential energy as well as in kinetic energy constituents in relation to the group of healthy children. These changes constitute standard ranges and can be used as a comparative tool for results concerning children with various neurological and orthopaedic dysfunctions.
2. The article presents the ranges of changes in mechanical and potential energy as well as in kinetic energy constituents in relation to the 56-strong group of patients with cerebral palsy. In terms of the patients with *CP*, it was demonstrated that the analysis of the mean values of changes in individual constituents of kinetic energy was particularly important. The children with cerebral palsy revealed more than twice higher mean value of changes in kinetic energy in relation to transverse axis ΔE_{kx} in comparison with the standard.
3. The research revealed the existence of statistically relevant differences between the values of the *GGI*, *GDI* and *EE* in relation to the control group and to the patients with cerebral palsy.
4. The 56-strong group of patients with cerebral palsy was characterised by a relatively strong statistically relevant dependence between the *GGI* and *EE* (0.74) and between the *GDI* and the *EE* (–0.68). It was ascertained that the index of energy expenditure (*EE*) could be a useful tool when diagnosing patients with locomotion function disorders.
5. The research did not reveal the existence of statistically relevant differences between the results of the *EE* index obtained in the initial test and in the test performed 6 months following the administration of botulinum toxin, yet, the above-mentioned analysis involved a small number of patients. The research-related conclusions indicated the necessity of the development of tests involving the analysis concerning the similarities of the profiles of energy variables in order to identify their convergence in the relative time ranges of the gait cycle.

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