

Article

Application of the Gait Kinematics Index in Patients with Cerebral Palsy

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Abstract: Due to the complexity of the medical issues connected with cerebral palsy (CP), the classification of gait pathologies seems rather difficult. The aim of this study was to assess the usefulness of the Gait Kinematics Index (GKI) from a clinical point of view in the population of patients with CP. The assessment of the possibilities of using the GKI in a group of patients with CP was conducted on the basis of the correlation of its results with the Gillette Gait Index (GGI) and Gait Deviation Index (GDI) values. The distribution of the index values was also evaluated with attention paid to the CP types and treatment methods. Analyses were performed on the basis of the gait test results in a group of 56 healthy children and 72 patients with CP. The GKI values for patients with CP were 1.55 ± 0.66 , as opposed to 0.77 ± 0.17 for the reference group. A strong linear correlation was found between the values of the GKI and GGI ($r = 0.8 \div 0.85$), as well as between the GKI and GDI ($r = -0.89 \div 0.9$), obtained in children with CP. In addition, significant differences were found between the results obtained in all the groups of children with CP divided by treatment method (rehabilitation, botulinum, rhizotomy, $p < 0.05$), whereas in the groups of children divided by CP type, significant differences ($p < 0.05$) were found solely between diplegia and hemiplegia and between hemiplegia and quadriplegia. The results obtained were the same in the case of the GKI, GGI and GDI. To conclude, the results presented in this work confirm the clinical utility of the GKI in the population of patients with CP.



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1. Introduction

Children's cerebral palsy (CP) is one of the most frequent causes of motor disability in the child population. The global prevalence of CP is estimated at around 1.5 to 3 per 1000 live births [1,2]. This includes both cases that are diagnosed in the first year of life and those diagnosed later. The disease's severity, patterns of motor involvement and associated impairments, such as those of communication, intellectual ability and epilepsy, vary widely. Due to its clinical complexity and accompanying symptoms, cerebral palsy is divided into different types. There is a marked variability in the classification and function between individuals. For these reasons, patients with CP are taken care of by a multi-specialty team [3–7]. The classification of gait in patients with CP is very demanding; however, it is of great clinical importance. It enables the start of a proper treatment and makes it possible to avoid recurring problems. Depending on the CP type and its accompanying symptoms, a therapeutic method is selected, e.g., rehabilitation, pharmacological treatment (botulinum toxin, Intrathecal Baclofen Therapy—IBT), surgical treatment (Selective Dorsal Rhizotomy—SDR, or Selective Peripheral Neurotomy—SPN) [8–17]. Also, a significant role in this context is played by an objective analysis of gait based on data and not solely on observations. The different scales of functional assessment (e.g., the Gross Motor Function Classification System (GMFCS), Gross Motor Function Measure (GMFM), Pediatric

Evaluation of Disability Inventory (PEDI), Manual Ability Classification System (MACS), and Gillette Functional Assessment Questionnaire (FAQ)) are subjective, and results often depend directly on the testing person's experience and knowledge [18–21]. More and more often, motor functions in patients with motor system dysfunctions are assessed by means of quantitative methods, which are based, among other things, on optical systems for motion analysis. Such an analysis provides many variables, whose simultaneous evaluation is more often than not difficult and time-consuming. An optimum solution supporting this quantitative analysis seems to lie in the index methods, which assess gait using one numerical value (GGI, GDI) or, additionally, with diagrams showing deviations from standard gaits (the Gait Profile Score (GPS), GKI). Moreover, the GKI is equipped with an algorithm enabling the determination of a global indicator of symmetry [22–27]. The above-mentioned indices make use of various mathematical algorithms and are based on different kinematic parameters. The GGI is based on a selection of 16 time-space and kinematic parameters (mean values, ranges, minimum and maximum values), which, according to clinicians, accurately describe the gait of patients with CP. This index is expressed by means of a single numerical value. The value of the GGI is a measure of the difference between a set of discrete parameters of the gait of a given patient and the mean parameters of the gaits of healthy individuals [23]. The application of Principal Component Analysis makes it possible to avoid errors resulting from the codependence of some variables and the use of different units. On the basis of the GGI it is possible to evaluate how much a given patient's gait deviates from a regular gait (a healthy person's gait) [22]. Despite the fact that the GGI parameters are specifically dedicated to patients with CP, the GDI and GKI appear to be more objective due to the full image of the motion kinematics they provide throughout the whole gait cycle. The ability to assess the full range of motion is important, especially considering the number and variety of motor disorders resulting from brain injury. Using a single numerical value, the Gait Deviation Index (GDI) makes it possible to indicate the deviations between the gait of patients and healthy people. The GDI takes into consideration nine variable kinematic values describing a range of angles in the knee, hip, pelvic and tarsal joints [24]. The data are collected every 2% of the gait cycle, which amounts to 459 measuring points for one patient. The calculated GDI value provides information on the difference of the gait of a given patient from a regular gait. The gait of a tested person is similar to the gait of the control group where the $GDI \geq 100$, whereas each decrease of 10 in the GDI below 100 indicates one standard deviation from the mean calculated for the control group. The GDI has been applied multiple times to the assessment of locomotive functions in patients with CP [23–25]. The proposed GKI is based on eleven kinematic parameters recorded during gait examples, and provides information about changes in angles in the ankle, knee joint, hip joint and pelvic movements in three planes. The GKI values were identified on the basis of the GCI_i , assessing locomotor functions at each percentage of the gait cycle. The classification of the GCI_i values in accordance with the adopted color scale constituted the Gait Deviations Profile. The GDP can be used to indicate a patient's gait deviations from the standard in relation to each percentage of the gait cycle. Such an assessment is not possible using any other index described in available scientific publications. The method also enables a more precise assessment of gait, based on values of KI_j . Indices KI_j are calculated for each kinematic parameter (P1–P11) as the mean value of standardized angular variables W_{ji} related to a given parameter. Indices KI_j are also classified in accordance with the color scale. A new comprehensive method of gait pathology evaluation (the Gait Kinematics Index, Global Symmetry Index and Gait Deviations Profile) makes it possible to identify gait using a single numerical value, evaluate movements in individual joints and in subsequent moments, as well as to assess the symmetry of gait. A detailed characterization of this gait assessment method in relation to other indicator methods found in the literature is presented in Table 5 in Jochymczyk-Wozniak et al. [22]. The GKI is a new indicator that has not yet been used in the clinical evaluation of gait in patients with CP. The only indicator method other than the GKI that allows the assessment of gait on the basis of sub-parameters that characterize the

movement in a given joint is the GPS [27]. Partial values of the GPS presented in the form of a MAP (Movement Analysis Profile) are used for the comparison of nine kinematic parameters of the patient's gait (the same as those taken into consideration in the identification of the GDI), with the average values of the aforementioned parameters related to the group of persons with a proper gait. The above-named MAPs are presented in the form of a bar chart, on the basis of which it is possible to indicate deviations from the standard only in relation to a specific joint [22,27]. The advantages of the gait assessment method proposed by the authors presented in the color scale consist in showing a patient's deviations from the standard gait in each percentage of the gait cycle. Color profiles of deviations from the standard gait are presented in relation to each kinematic parameter (P1–P11) that was subjected to analysis. Such an analysis enables both a detailed and intuitive assessment of the patient's gait kinematics in each joint and at each percentage of the gait cycle [22].

The aim of this study was to assess the clinical utility of the GKI in the population of patients with CP. The possibilities of applying the GKI to a group of patients with CP were evaluated on the grounds of the correlation of its results with the GGI and GDI values. Also, the distribution of its values in terms of CP types and treatment methods was assessed.

Our hypothesis was that the GKI values of CP patients would be strongly correlated with the GDI values. We hypothesized that the GKI values of CP patients would also be moderately or strongly correlated with the GGI values. We also hypothesized that the GKI values would differ significantly between CP types and treatment methods.

2. Materials and Methods

2.1. Participants

An a priori sample size estimation/power analysis was performed in G*Power. To calculate a representative sample size for the ANOVA test/the Kruskal–Wallis ANOVA test involving three groups, the expected effect size (large 0.4), significance level ($\alpha = 0.05$), and statistical power ($1 - \beta = 0.80$) were calculated. Appropriate statistical formulas and data from previous studies [28] were used to calculate the minimum number of participants. These calculations aimed to ensure adequate statistical power to detect significant differences between the groups. G*Power indicated a total sample size of 66 participants. In the current study, 77 participants were recruited. This study was a single-cross-sectional study, which means that participants were assessed only once, without being re-examined. The study involved a reference group and a group of patients with cerebral palsy, and was conducted at the Upper Silesian Children's Health Centre (USCHC) in Poland. Participants were recruited in the hospital. The recruitment process was systematic and in accordance with the ethical standards of clinical research. Patients with CP were recruited from the hospital's patient database, including those already receiving hospital treatment. Patients who met the initial eligibility criteria were informed about the study by telephone or in a face-to-face interview with a doctor or member of the research team. The patient qualification assessment was carried out by the doctors of the USCHC.

Inclusion criteria for the reference group were as follows: age between 30 months and 18 years, no musculoskeletal disorders (medically qualified for the study), and a written consent to participate in the study by a parent/guardian.

The following criteria were used to select patients with CP for the study group: age of patients in all groups—from 30 months to 18 years—diagnosed with cerebral palsy in the form of spastic syndrome (diagnosis based on the clinical picture and results of neuroimaging examinations), patients rehabilitated and treated with botulinum toxin, patients qualified for the procedure of selective rhizotomy of dorsal roots, patients qualified for at least level II on the GMFCS scale, parental consent obtained for gait testing, and patients walking independently and in cooperation. Patients under 30 months of age, patients diagnosed with motor disorders other than cerebral palsy, patients using lower limb orthoses and unable to walk without orthoses, non-rehabilitated patients, and uncooperative patients were excluded from the study group. This study was approved by

the ethical committee of the Medical University of Silesia in Katowice (protocol number KNW/0022/KB1/19/11).

The testing group consisted of 56 healthy children—without dysfunctions of the motor system (28 boys and 28 girls)—as well as 72 patients with CP (45 boys and 27 girls). The reference group (the healthy group) was composed of 56 healthy children aged 11 ± 3 y.o., body mass: 41.8 ± 13.2 kg and body height: 147 ± 17 cm. The age of children with CP was 9 ± 4 y.o., body mass: 29.3 ± 13.7 kg and body height: 128.73 ± 22.3 cm.

The patients were divided in terms of CP type—diplegia (43 patients), hemiplegia (17 patients) or quadriplegia (12 patients)—as well as in terms of treatment methods: children subjected solely to rehabilitation (12 patients), botulinum toxin injection procedures (43 patients) or qualified for the procedure of selective rhizotomy of dorsal roots (17 patients).

2.2. Experimental Testing

The patients underwent a medical assessment (neuromuscular tests) and a biomechanical one (gait test). The tests were performed at the Motion Analysis Laboratory using a system enabling the BTS Smart (BTS S.p.A., Milan, Italy) triplanar motion analysis. The BTS system consisted of six IR cameras, allowing for the recording of the location of passive markers in space (sampling rate of 250 Hz), a camera capturing video images, two dynamometric platforms (Kistler Eastern Europe s.r.o., Prague, Czech Republic, sampling rate of 1000 Hz), and a control unit provided with a software program to coordinate the operation of the entirety of the measurement equipment. Using a device for system calibration, the measurement path was connected to 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 the X-axis as the motion of the center of gravity of the body on the transverse axis (motion in the right and left direction), the motion on the Z-axis as the motion in the direction of the sagittal axis, and the motion along the vertical Y-axis as the up-and-down motion. The BTS Smart system, which is based on optical analysis, requires cameras to be calibrated. To accurately calibrate the cameras and markers in 3D space, a wand calibration was used. During calibration, the wand was moved in different directions (X, Y, Z axes) and angles, performing slow and rotational movements to ensure full coverage of the cameras' field of view. A satisfactory calibration result is attained when the calibration error is less than 1mm for spatial measurements, ensuring the highly accurate tracking of markers in space.

The location of the markers (15 spherical motion capture markers covered with a reflective material with a diameter of 1.5 cm) complied with the Helen Heyes protocol [29] (Figure 1). A model built in the BTS System was used for the calculations. The markers were placed by the same person with 15 years of experience working with motion capture technology, ensuring high-quality and reproducible results.

Before the commencement of the gait test, the necessary anthropometric measurements were made in accordance with the Davis model, and then each child covered the measurement path (7 m) ten times barefoot. Two complete gait cycles were analyzed from each gait trial, taken from the middle part of the measurement path. This meant that cycles from the acceleration and deceleration phases were not included in the analysis. On average, 20 gait cycles were analyzed per study participant. In further analysis, the average of all strides for each child was used. During the tests, the children moved at their natural velocity. For each subject, 2–3 static (standing) trials were recorded.

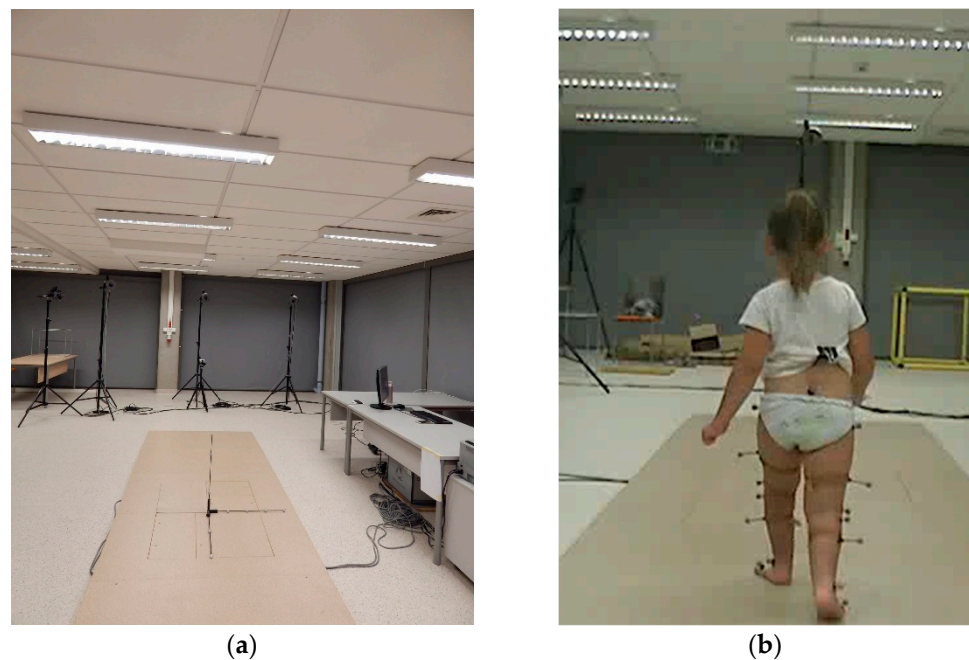


Figure 1. (a) Measurement stand BTS Smart, (b) patient during measurements.

2.3. Data Processing

In the case of data collected using BTS, the initial reconstruction and auto-labeling of marker trajectories were conducted in the BTS Smart Tracker. Each trial was subsequently visually inspected, and any unmarked trajectories were labeled manually. Two algorithms were used to correct gaps in the trajectories, which are available to use in the protocols of the BTS Smart system: interpolating an object track using cubic spline curves and smoothing an object track using a triangular window filter. These processes resulted in an accurate 3D model of gait [30]. Gait cycles were defined using data from the BTS, ranging from the first right-foot heel strike to the subsequent heel strike on the same side. The moment of contact between the foot and the ground was indicated when the force vector appeared on the dynamometer platforms. If the participant did not hit the platform with the foot, a heel strike was identified as the local minimum in the anterior-posterior position of the heel relative to the sacrum. The complete gait cycles were normalized in terms of time separately for each lower limb. The joint angles and pelvic alignment were normalized to the gait cycle separately for the right and left lower limbs.

2.4. Calculation of Gait Indicators

A detailed mathematical algorithm of the GKI was presented in the study by Jochymczyk-Woźniak et al. [22]. On the basis of the recorded parameters, a series of space-time parameters and kinematic quantities was obtained. Furthermore, using original applications written in the Matlab environment, the following gait indices were calculated: GKI [22], GGI [23], and GDI [24]. The GKI is a new tool that has not been applied before to the assessment of gait in patients with CP. The GKI is devised on the basis of time courses of 11 kinematic parameters of gait j expressed in degrees (j —number representing the following 11 kinematic parameters of the gait: PTILT—pelvic tilt, POBLI—pelvic obliquity, PROT—pelvic rotation, HPFE—hip flexion-extension, HPAA—hip abduction-adduction, HPIE—hip rotation, KFE—knee flexion-extension, KAA—knee valgus-varus, KIE—knee rotation, AFE—ankle dorsal-plantar flexion, and AIE—foot progression). For each kinematic value j , researchers calculated the absolute value of the difference between the value obtained for a given patient and the mean value obtained in the case of the norm in each gait cycle percentage i . Partial indicator W_{ji} is a quotient of the obtained difference and the value of standard deviation of a given kinematic value obtained for the norm. For each

kinematic value j , the kinematic index of gait KI_j is calculated, which is an arithmetic mean of partial indices W_{ji} obtained in successive gait cycle percentages and for a given value of j . In each gait cycle percentage, separately for the right and left limb, the Gait Cycle Index GCI_i is also calculated. The GCI_i is an arithmetic mean of partial indices W_{ji} obtained for all kinematic values j in a given gait cycle percentage i . As a result, 101 GCI_i are obtained for the right lower limb and 101 GCI_i for the left lower limb. The Gait Kinematic Index (GKI) is an arithmetic mean of the GCI_i obtained in subsequent gait cycle percentages i . It is calculated separately for the right and left lower limb. To facilitate the analysis of results, a color scale was devised, which enables a visual classification of the values of partial indices W_{ji} , K_{ij} , and the GKI values. The scale was divided into four levels: results in the norm (green color), results at the limit of the norm (yellow color), results beyond the norm (orange color), results significantly beyond the norm (red color) (Tables 1 and 2). The ranges of particular levels of the color scale in the case of W_{ji} , K_{ij} , and the GKI were selected on the basis of results obtained in the group of healthy children (mean values and successive deviations from the norm).

Table 1. Classification of results W_{ji} , GKI.

Color	Value	Evaluation of Results
Green $W_{ji} \leq 1$ $GKI \leq \text{mean} \pm \text{std}$	$W_{ji} \leq 1$ $GKI \leq 1.01$	Results in the norm
Yellow $1 < W_{ji} \leq 2$ $\text{mean} \pm \text{std} < GKI \leq \text{mean} \pm 2 \times \text{std}$	$1 < W_{ji} \leq 2$ $1.01 < GKI \leq 1.24$	Results at the limit of the norm
Orange $2 < W_{ji} \leq 3$ $\text{mean} \pm 2 \times \text{std} < GKI \leq \text{mean} \pm 3 \times \text{std}$	$2 < W_{ji} \leq 3$ $1.24 < GKI \leq 1.47$	Results beyond the norm
Red $W_{ji} > 3$ $\text{mean} \pm 3 \times \text{std} < GKI$	$3 < W_{ji}$ $1.47 < GKI$	Results significantly beyond the norm

W_{ji} —standardized angular variable, GKI—Gait Kinematic Index, std—standard deviation.

Table 2. Classification of results KI_j .

j	Green Results in the Norm $KI_j \leq \text{mean} \pm \text{std}$	Yellow Results at the Limit of the Norm $\text{mean} \pm \text{std} < KI_j \leq \text{mean} \pm 2 \times \text{std}$	Orange Results Beyond the Norm $\text{mean} \pm 2 \times \text{std} < KI_j \leq \text{mean} \pm 3 \times \text{std}$	Red Results Significantly Beyond the Norm $KI_j > \text{mean} \pm 3 \times \text{std}$
AFE	$KI_j \leq 1.45$	$1.45 < KI_j \leq 2.09$	$2.09 < KI_j \leq 2.72$	$2.72 < KI_j$
AIE	$KI_j \leq 0.58$	$0.58 < KI_j \leq 0.83$	$0.83 < KI_j \leq 1.09$	$1.09 < KI_j$
KFE	$KI_j \leq 1.56$	$1.56 < KI_j \leq 2.24$	$2.24 < KI_j \leq 2.91$	$2.91 < KI_j$
KAA	$KI_j \leq 1.31$	$1.31 < KI_j \leq 1.90$	$1.90 < KI_j \leq 2.49$	$2.49 < KI_j$
KIE	$KI_j \leq 1.59$	$1.59 < KI_j \leq 2.30$	$2.30 < KI_j \leq 3.02$	$3.02 < KI_j$
HPFE	$KI_j \leq 1.49$	$1.49 < KI_j \leq 2.10$	$2.10 < KI_j \leq 2.72$	$2.72 < KI_j$
HPAA	$KI_j \leq 1.68$	$1.68 < KI_j \leq 2.38$	$2.38 < KI_j \leq 3.08$	$3.08 < KI_j$
HPIE	$KI_j \leq 1.59$	$1.59 < KI_j \leq 2.28$	$2.28 < KI_j \leq 2.97$	$2.97 < KI_j$
PTILT	$KI_j \leq 1.40$	$1.40 < KI_j \leq 2.02$	$2.02 < KI_j \leq 2.63$	$2.63 < KI_j$
POBLI	$KI_j \leq 1.28$	$1.28 < KI_j \leq 1.86$	$1.86 < KI_j \leq 2.43$	$2.43 < KI_j$
PROT	$KI_j \leq 1.07$	$1.07 < KI_j \leq 1.55$	$1.55 < KI_j \leq 2.02$	$2.02 < KI_j$

j —one of the 11 kinematic gait parameters, KI_j —gait kinematic index, j —kinematic parameter of gait subjected to analysis, std—standard deviation, PTILT—pelvic tilt, POBLI—pelvic obliquity, PROT—pelvic rotation, HPFE—hip flexion-extension, HPAA—hip abduction-adduction, HPPIE—hip rotation, KFE—knee flexion-extension, KAA—knee valgus-varus, KIE—knee rotation, AFE—ankle dorsoplantarflexion, AIE—foot progression.

The key dependent variables for this study were 11 gait kinematic values (PTILT—pelvic tilt, POBLI—pelvic obliquity, PROT—pelvic rotation, HPFE—hip flexion-extension, HPAA—hip abduction-adduction, HPPIE—hip rotation, KFE—knee flexion-extension, KAA—knee valgus-varus, KIE—knee rotation, KAA—knee valgus-varus, KIE—knee rotation, AFE—ankle dorsal-plantar flexion, AIE—foot progression), which were used to calculate the GKI

and the values of the GGI, GDI, and GKI. The independent variables for this study were CP type and treatment methods.

2.5. Statistical Analysis

The numerical values of the GGI, GDI, and GKI indices obtained in the group of healthy participants and patients with CP are presented in tables and expressed as mean and standard deviation, median, as well as minimum and maximum values.

The normality of the distribution of the analyzed data was assessed using the Shapiro–Wilk test. In order to verify the degree of dependence between the values of the GKI and GDI as well as between the GKI and GGI, the researchers assessed the degree of Pearson’s linear correlation coefficient. The usual scale for correlation coefficients was used for the interpretation of r values: 0.0–0.1—trivial; 0.1–0.3—small; 0.3–0.5—moderate; 0.5–0.7—large; 0.7–0.9—very large; and 0.9–1—nearly perfect [30]. The distribution of results is presented in the scatter plots. The equations of a simple linear regression with coefficient of determination R^2 were also calculated.

To compare the differences between gait indices in the group of patients analyzed in terms of CP types and treatment methods, either the ANOVA test, using one independent variable, or the Kruskal–Wallis test was conducted, depending on the normality of the distribution of the analyzed data. All statistical analyses adopted a significance level $p = 0.05$. Statistica 13.1 software was used for all statistical analyses.

3. Results

3.1. Index Analysis of Gait in Children Without Motor System Dysfunctions

To aid the analysis of the results, a color scale was created to visually classify the values of the W_{ji} , K_{ij} and GKI. The scale is divided into four levels: results within the normal range (green), results at the threshold of the normal range (yellow), results exceeding the normal range (orange) and results significantly exceeding the normal range (red). The ranges of particular levels of the color scale for W_{ji} , K_{ij} and values of the GKI were calculated on the basis of the results obtained in the reference group (mean values and successive deviations from the standard) and are presented in Tables 1 and 2.

Table 3 presents the averaged values of the GKI, standard deviation, median, minimum and maximum values obtained in the reference group (the healthy group). The results were collated with the obtained values of the GGI and GDI (Table 3). The results of Pearson’s linear correlation between the values of the GKI and GGI, as well as the GDI, in the case of the reference group are presented in Table 4.

Table 3. Mean, standard deviation, minimum and maximum value of the GKI, GGI, and GDI obtained in the reference group.

Gait Index	Mean	Standard Deviation	Minimum Value	Maximum Value
GKI	0.77	0.17	0.44	1.22
GGI	15.71	5.68	7.46	30.00
GDI	99.23	8.37	78.95	121.07

GKI—Gait Kinematic Index. GGI—Gillette Gait Index, GDI—Gait Deviation Index.

Table 4. Pearson’s correlation coefficients between the GKI and GGI, as well as the GDI, in the reference group.

	GGI	GDI
GKI	0.29	−0.73

GKI—Gait Kinematic Index. GGI—Gillette Gait Index, GDI—Gait Deviation Index.

Red-marked correlation coefficients (Table 4) are statistically significant ($p < 0.05$), which means that a zero hypothesis about the lack of dependence between the selected

indices can be rejected. On the grounds of the Pearson correlation results, it can be stated that between the values of the GKI and GGI, there is a low linear dependence, whereas between the GKI and GDI, there is a negative strong linear correlation. As GKI values increase, GDI values tend to decrease. The above-described correlations are presented in scatter plots in Figure 2a,b.

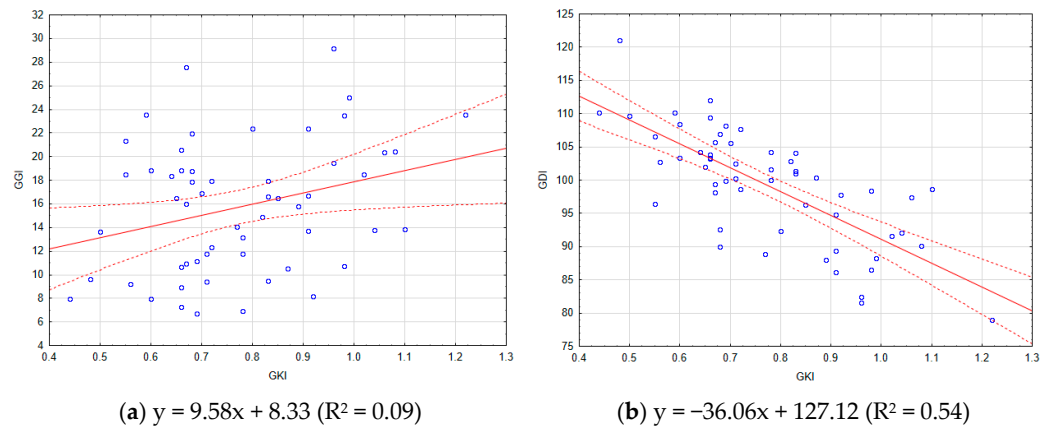


Figure 2. Scatter plot depicting dependence between indices, regression equations, and R^2 values: (a) GKI and GGI and (b) GKI and GDI.

3.2. Index Analysis of Gait in Patients with CP

Following the analysis of the normative values of the GKI, this index was determined for the reference group with CP. It was also collated with results obtained in the case of the GGI and GDI. Table 5 contains averaged data, standard deviation as well as minimum and maximum values.

Table 5. Mean, standard deviation, minimum and maximum values of the GKI, GGI and GDI obtained in the group of children with CP.

Gait Index	Mean	Standard Deviation	Minimum Value	Maximum Value
GKI	1.55	0.66	0.64	4.26
GGI	488.88	581.75	27.18	3188.9
GDI	73.11	12.81	31.76	101.72

GKI—Gait Kinematic Index, GGI—Gillette Gait Index, GDI—Gait Deviation Index.

The scatter of the values obtained in the analyzed group of ill individuals reveals a wide spectrum of disorders that may occur in patients with CP. Due to this fact, the children were divided into sub-groups, and the obtained values of indices were presented in Tables 6 and 7.

The mean obtained in the group of children with CP (Table 5) for the GKI (1.55 ± 0.66), and, in particular, the GGI (488.88 ± 581.75), is higher in comparison to the values obtained in the reference group (0.77 ± 0.17 , 15.71 ± 5.68 , respectively) (Table 3). In addition, the standard deviation of the GGI is higher than its arithmetic mean, which shows how diverse the trial is. In the case of the GDI, average results were obtained below 100, which confirms the dysfunction of gait. The scatter of the values obtained in the analyzed group of ill individuals signifies a wide spectrum of disorders that can occur in patients with CP. Due to this fact, the division of the children into specific sub-groups was performed (Tables 6 and 7). Taking into consideration the results presented with the division into treatment methods, it can be stated that the highest mean deviation of gait from the norm, as well as the differences between minimum and maximum values in the case of all indices, were obtained in children qualified for the procedure of selective rhizotomy of dorsal roots. An exactly opposite situation takes place in the case of individuals subjected to

rehabilitation, where the results obtained in some patients fall into the norm. As far as the form of the cerebral palsy in children is concerned, the mean value of indices that was the furthest from the norm was obtained in patients with quadriplegia, whereas the closest value to the norm was in patients with hemiplegia. In the case of the GKI and GDI, the differences between minimum and maximum values were comparable and, at the same time, lower than in a homogeneous group of ill individuals. In addition, in the case of the GKI, each of the three sub-groups included patients who were included in the norm of a given indicator. Taking into account the GGI, one may notice that children with hemiplegia obtained a clearly smaller scatter in comparison with diplegia and quadriplegia. Simultaneously, the scope of values obtained in these patients was also not higher than in a homogeneous group. Comparing indices with each other, the greatest diversification of results, as in the case of the reference group, can be observed in the case of the GGI, whereas the smallest diversification is observed in the case of the GDI.

Table 6. Mean, standard deviation, minimum and maximum values of the GKI, GGI and GDI obtained in the group of children with CP with division into treatment methods.

Gait Index	Patient Group	Mean	Standard Deviation	Minimum Value	Maximum Value
GKI	Rehabilitation	0.94	0.26	0.64	1.63
	Botulinum	1.44	0.44	0.8	2.45
	Rhizotomy	2.22	0.76	0.92	4.26
GGI	Rehabilitation	110.80	145.27	27.18	571.46
	Botulinum	347.21	330.31	33.06	1477
	Rhizotomy	1114.12	782.17	63.58	3188.9
GDI	Rehabilitation	88.19	7.40	74.53	101.72
	Botulinum	73.56	9.46	52.97	90.7
	Rhizotomy	61.29	11.53	31.76	82.84

GKI—Gait Kinematic Index, GGI—Gillette Gait Index, GDI—Gait Deviation Index.

Table 7. Mean, standard deviation, minimum and maximum values of the GKI, GGI and GDI obtained in the group of children with CP with division into CP types.

Gait Index	Patient Group	Mean	Standard Deviation	Minimum Value	Maximum Value
GKI	Diplegia	1.42	0.44	0.69	2.45
	Hemiplegia	1.07	0.40	0.64	2.43
	Quadriplegia	1.57	0.39	0.84	2.19
GGI	Diplegia	344.14	358.59	33.06	1477
	Hemiplegia	134.25	71.66	27.18	285.44
	Quadriplegia	456.66	327.67	95.2	1229.9
GDI	Diplegia	74.70	9.58	55.01	96.3
	Hemiplegia	84.02	9.44	56.72	101.72
	Quadriplegia	69.03	10.06	52.97	85.03

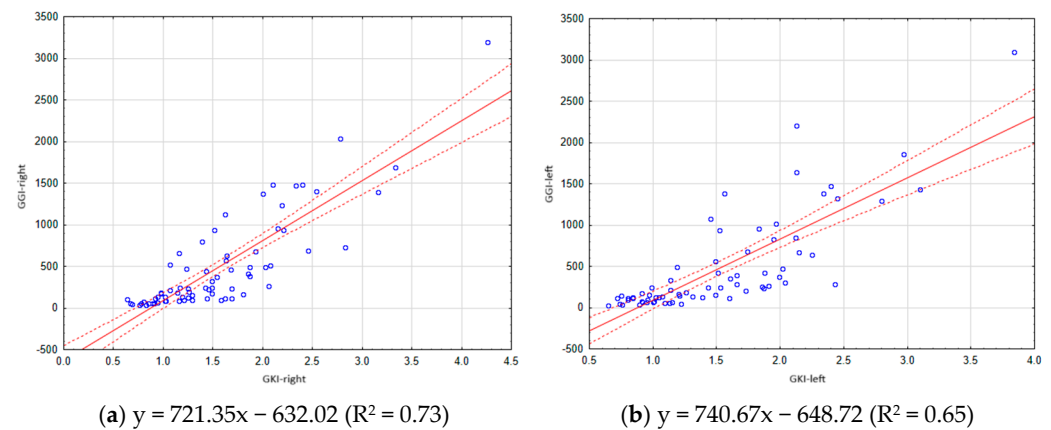
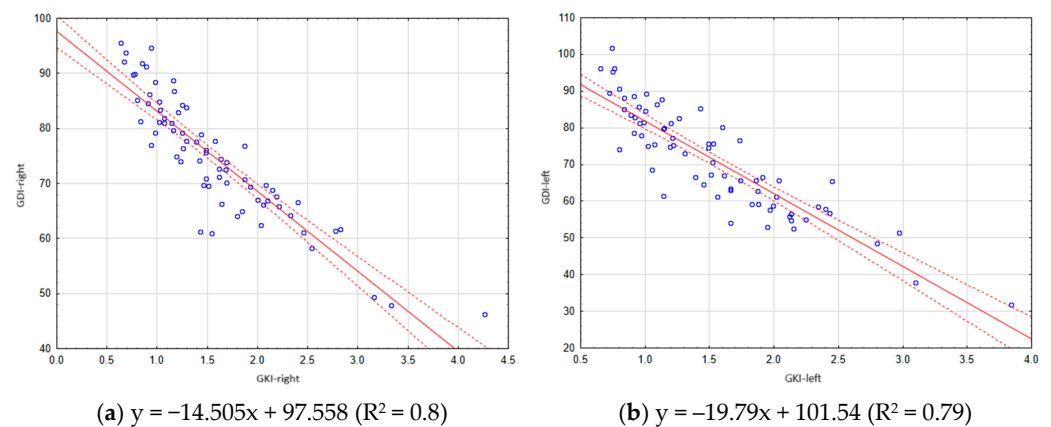
GKI—Gait Kinematic Index, GGI—Gillette Gait Index, GDI—Gait Deviation Index.

The results of Pearson's correlations between the values of the GKI and GGI, as well as the GDI, in the group of patients with CP are presented in Table 8. All red-marked correlation coefficients (Table 8) are statistically significant ($p < 0.05$), which means that, similar to the case of the reference group, we can reject the zero hypothesis about the lack of dependence between the analyzed indices. On the basis of the results of Pearson's correlations, it can be stated that all selected indices strongly correlate with one another. A strong, statistically significant linear dependence was found between the values of the GKI, GGI and GDI in the group of patients with CP. The described dependences are presented in scatter plots in Figures 3 and 4. Below the scatter plots are the equations of a simple linear regression with a coefficient of determination R^2 .

Table 8. Pearson’s correlation coefficients between the GKI and GGI, as well as the GDI, in the group of patients with CP with division into the right and left lower limb.

	GGI—Right	GGI—Left	GDI—Right	GDI—Left
GKI—right	0.85		−0.90	
GKI—left		0.80		−0.89

GKI—right/left—Gait Kinematic Index designated for right or left lower limb, GGI—Gillette Gait Index designated for right or left lower limb, GDI—Gait Deviation Index designated for right or left lower limb.

**Figure 3.** Scatter plot presenting dependence between the GKI and GGI, regression equations and R^2 values in the case of (a) right lower limb in patients with CP and (b) left lower limb in patients with CP.**Figure 4.** Scatter plot presenting dependence between the GKI and GDI, regression equations and R^2 values in the case of (a) right lower limb in patients with CP and (b) left lower limb in patients with CP.

Either the performed ANOVA test using one independent variable or the Kruskal–Wallis test proved that the values of all gait indices, i.e., the GGI, GDI and GKI, obtained in patients with CP statistically significantly differ in the group of patients divided into CP types and treatment methods ($p < 0.05$). The performed post-hoc tests showed that the values of all gait indices significantly differ between all subgroups of patients who were qualified for different methods of treatment ($p < 0.05$). The conducted post-hoc tests also showed statistically significant differences of all indices between the values obtained in the groups of patients with diplegia and hemiplegia, as well as between hemiplegia and quadriplegia, and the lack of differences between diplegia and quadriplegia (Figure 6). The distribution of results of the GGI, GDI and GKI in the analyzed sub-groups is presented in Figures 5 and 6.

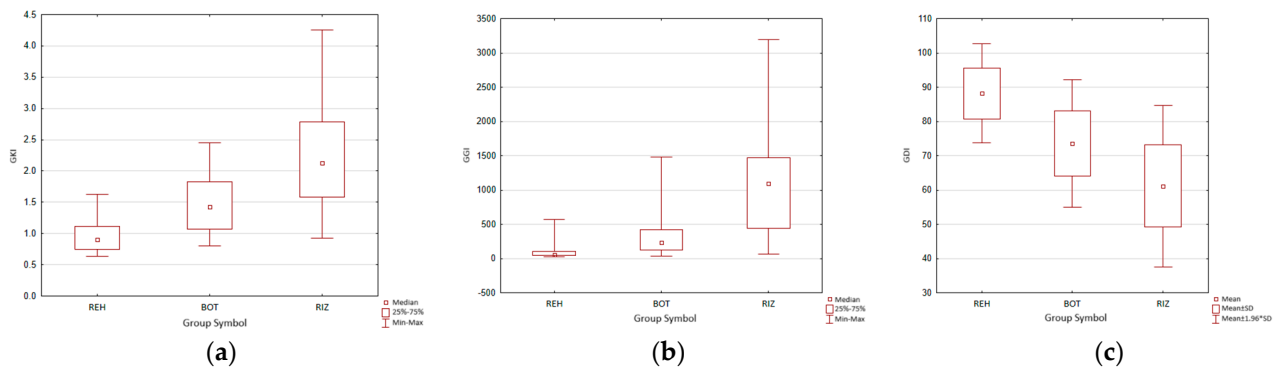


Figure 5. Distribution of results of (a) GKI, (b) GGI and (c) GDI in children treated with the different methods.

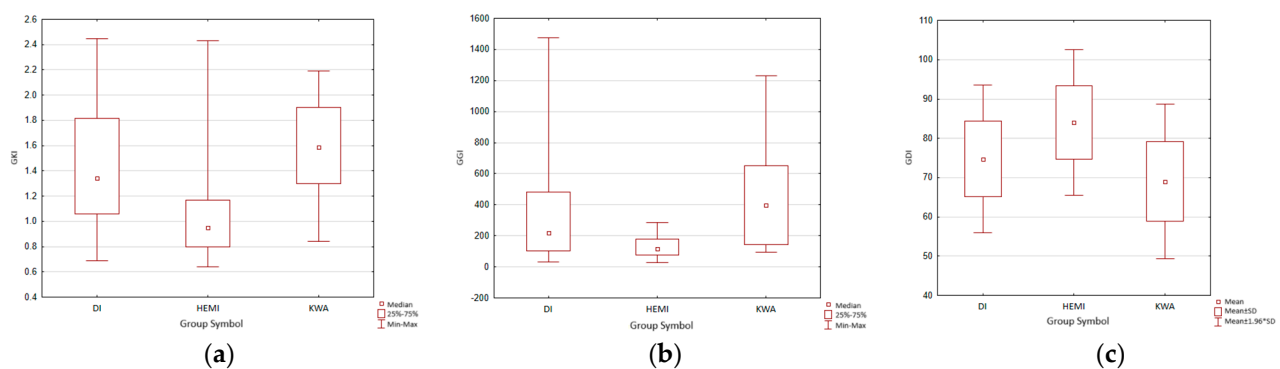


Figure 6. Distribution of results of (a) GKI, (b) GGI and (c) GDI in children with different CP types.

4. Discussion

Gait indices, such as the Gait Index and the Gait Deviation Index, are used clinically to assess patients' gait quality. There is a need for the development of further gait indices to better understand the complexity of movement and to match therapies to individual patients' needs, which can contribute to more effective rehabilitation and improved quality of life. The GKI is one of the new gait indicators that have been proposed, but it has not yet been evaluated for clinical use.

The main objective of this study was to assess the clinical utility of the GKI in the population of patients with CP. The possibilities of the application of the GKI to the group of patients with CP were assessed on the basis of the correlation of its results with the GGI and GDI values. In addition, the distribution of the GKI values was evaluated in terms of the CP type and method of treatment. The results obtained confirmed the hypothesis that the GKI values of CP patients strongly correlated with the GDI values. This is due to the fact that these indicators are based on the same parameters—i.e., the time courses of the kinematics of the movement of lower limbs and the pelvis. It also confirmed the hypothesis that the GKI values of CP patients are strongly correlated with the GGI values. The analysis of the results showed that the GKI values differed significantly according to the type of CP and the treatment method. The analysis of the obtained data showed that the values of the GKI in all children in the reference group (without dysfunction of the motor system) do not considerably diverge from one another (Table 3). The largest scatter of the values can be observed in the case of the GGI (Figure 2a), whereas the smallest can be observed in the case of the GDI (Figure 2b). The difference in the orders of magnitude of values between the indices results from the fact that they are built from different parameters and algorithms [22–24].

Taking into consideration the division of children in terms of methods of treatment, the results obtained in the three sub-groups (rehabilitation, botulinum, rhizotomy) significantly differ from one another in each indicator ($p < 0.05$; Figure 5). Statistically significant differences in all gait indices were also observed in the case of the division of patients in terms of CP types ($p < 0.05$). The analysis of the distribution of results obtained in the groups of patients divided into CP types revealed statistically significant differences between diplegia and hemiplegia as well as between hemiplegia and quadriplegia; however, it showed the lack of differences between diplegia and quadriplegia (Figure 6). Also, the authors of other works have indicated the presence of statistically significant differences in the case of the GGI and GDI in the group of patients with different types of CP [17,24,27]. The values of the GKI in patients with different forms of CP are distributed in a similar way to the values of the GDI and GGI. This fact suggests that the GKI may carry similar clinical information about gait to the indices that have been already applied to the clinical assessment. On the basis of the Pearson correlation results obtained in the reference group, it can be stated that between the GKI and GGI there is a weak dependence, whereas between the GKI and GDI there is a strong linear correlation. This fact makes it possible to conclude that the GKI carries proper clinical information and may be useful in the assessment of gait in patients with CP.

Researchers dealing with gait analysis in patients with CP point to the possibility of using gait indices in the assessment of treatment and rehabilitation progress [25,31]. What seems essential, however, is the verification of which of the indices constitutes the most sensitive measure for the evaluation of differences before and after the treatment of patients with CP. McMulkin et al. [25] made an attempt to compare the GGI, GDI and GPS/GDI* (designation of the transformed GPS as the GDI*) values in the population of individuals with typical pathologies of gait (seven groups of patients with various types of gait pathologies who were subjected to surgical procedures) in order to assess the sensitivity of the indices and their clinical significance. The aforementioned authors found that the most sensitive indices in terms of the evaluation of differences before and after treatment are the GDI and then the GPS/GDI*, whereas the GGI has nonparametric properties and its results are difficult to interpret intuitively [25,31].

The results of this study have shown that the new GKI is sensitive to the differences in the values in terms of the types of CP and the level of dysfunctions (qualification for different methods of treatment). The successive stage of this research should verify the possibilities of applying the GKI to the assessment of treatment/rehabilitation progress. It should also verify the index sensitivity in the evaluation of differences before and after treatment.

In spite of the great contribution that all the gait indices represent for clinical assessment, one should be critical of them and remember the limitations of these methods. The already known gait indices are characterized by complicated mathematical algorithms. Nearly all the indices enable the evaluation of gait using one non-dimensional numerical values. [23,24,27]. Nevertheless, gait indicators are used in clinical practice [32,33]. Doubts concerning the clinical application of gait indexes can be found in scientific publications by other authors [25,34]. According to Molloy M. et al., the assessment of locomotor functions based on a single numerical value lacks information about movement in individual joints and successive moments [26]. Taking into consideration the doubts raised with respect to the evaluation of gait based on a single numerical value and the fact that it does not provide a complex diagnostic method, it seems that the new comprehensive method of gait pathology evaluation—the Gait Kinematics Index, Global Symmetry Index and Gait Deviations Profile—can find applications in clinical establishments and movement analysis laboratories. However, it should not be forgotten that the limitation in indicator methods is the arbitrary selection of parameters, which takes into consideration only kinematic values and omits kinetic and electromyographic data. Gait indices are sensitive to the results obtained in the control group. Such results are specific to each laboratory, which may affect the differences in the mean values and result in an oversight of significant gait changes

in patients [17,23,24,34]. The aforementioned limitation should be taken into account in any research using index methods. In the near future, not only will new index methods be applied to the clinical assessment of gait, but methods based on Artificial Intelligence (AI) will also be applied. The authors fully realize the limitations of this study. Undoubtedly, a different number of individuals in particular groups constitutes a limitation. This was caused by the specific nature of CP and the fact that the researchers tested all patients who were under the care of the USCHC at the time of the study, without without having influence on the type of a patient. As a result, the particular groups divided based on forms of CP and methods of treatment did not have a uniform number of patients.

5. Conclusions

The analyses conducted showed that children with CP obtain higher values of the GKI and the GGI and lower values of the GDI in comparison to the reference group, which reveals the dysfunction of their gait. A strong linear correlation was found between the values of the GKI, GGI and GDI obtained in children with CP. However, in the case of values obtained in the reference group, a linear correlation was found solely between the GKI and GDI. Significant differences were revealed between the results obtained in all the groups of children with CP divided by treatment method (rehabilitation, botulinum, rhizotomy), whereas the groups of children divided by CP type showed significant differences only between diplegia and hemiplegia, as well as between hemiplegia and quadriplegia. The results obtained were the same in the case of the GKI, GGI and GDI.

To conclude, the results presented in this study confirm the clinical utility of the GKI in the population of patients with CP. The GKI generates properly dependent values, in comparison with the previously applied GGI and GDI, and their scatter should enable an easier and quicker interpretation of the obtained gait results.

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