

Integral method (IM) as a quantitative and objective method to supplement the GMFCS classification of gait in children with cerebral palsy (CP)

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Gait analysis is an objective tool for the clinical assessment of locomotor activity in children with cerebral palsy (CP). Correct diagnosis and properly planned rehabilitation are necessary for enhanced motor functions in persons suffering from cerebral palsy. Orthoses, orthopedic operations, medications and physiotherapy are the most common treatments. However, there is still a lack of objective methods for assessing motor behavior and monitoring the progress of recovery. The aim of the study was to use the ground reaction force patterns generated during walking to create the Integral Method (IM), which could become an objective tool that could supplement the functional classification of CP children based on the Gross Motor Function Classification System (GMFCS). A total of 15 healthy children and 34 children with CP who walk independently participated in the study. A Kistler force plate and GRFintegral software were used. Of the 34 measurements based on the IM for CP children, 17 matched the level assigned by the GMFCS, 2 children were assigned a higher level, and 15 were assigned a lower level. Pearson's correlation coefficient between the IM and the GMFCS was moderate ($r = 0.61$, $p \leq 0.01$). Asymmetry was found in 11 cases. The IM supplements the GMFCS and is an objective and quantitative assessment of motor abilities. The method allows for the detection of asymmetry, diagnosis of the improvement of gait pattern and assessment of foot support technique. With the appropriate software, the IM provides pediatricians, neurologists, orthopedists, surgeons and physiotherapists with a simple and fast way to assess gait.

Key words: children walking, cerebral palsy, ground reaction forces

1. Introduction

Over the last 40 years, the number of children born with cerebral palsy (CP) has increased to more than 2 every 1000 births [9]. Motor disturbances are some of the significant clinical symptoms of cerebral palsy in children, which are manifested as abnormal and non-independent walking. Strong dynamic contractures of thigh and shank muscles limit locomotor movements in these children and result in abnormal functioning of the hip, knee and ankle joints and consequently in abnormal feet movements and toe walking [5]. Perturbations of components of the ground reaction forces ensue as a result [13], [21], [23]. Abnormal movements of the

trunk, head and upper limbs, which generate abnormal inertia forces, influence the measured ground reaction force. Among the factors influencing the ground reaction forces in walking are velocity [14], [16], age [3], body mass and height [1]. A variety of complex methods have been used to interpret components of the ground reaction forces in walking [7], [8], [22], [24]. There is an enormous demand for quantitative methods that can assess walking ability [12] and monitor progress during the rehabilitation of CP children. A detailed but qualitative and subjective classification of CP children called the Gross Motor Function Classification System (GMFCS) [10] is widely used today.

The aim of this study was to use the ground reaction force patterns generated during walking to create

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the integral method (IM), which could become an objective tool to supplement the functional classification of CP children based on the commonly used GMFCS system. An indirect aim was to find similarities and differences in the information obtained from the IM and GMFCS methods and present arguments supporting the supplementation of the GMFCS with the IM. A functional assessment of CP children could easily be used in a quantitative way by pediatricians, neurologists, orthopedists, surgeons and physiotherapists, with particular focus on centers that do not have gait analysis systems but are equipped with dynamographic platforms.

2. Materials and methods

2.1. Children involved in the study

The study was approved by the Senate Commission for Ethics in Scientific Research of the University School of Physical Education. Parents and guardians were informed about the procedures and expressed their consent. The subjects participating in the study included 34 CP children (28 with diplegia and 6 with hemiplegia) from the Center for Rehabilitation and Neuropsychiatry who walk independently and fifteen 7-year-old healthy children. The reason why 7-year-old children were selected was that walking patterns are already mature in healthy children of that age [18]–[20]. The youngest CP child was 8, and the oldest was 16 years old. The group of CP children was so diverse in terms of age because chronological age differs from functional age in these children, with the latter being defined by the GMFCS [10]. The CP children were undergoing therapy prescribed by their doctors supplemented with another therapy that involved the Mechanical Home Pony [4]. The mean age (A), body mass (m), body height (h), walking speed (v), and standard deviation (SD) in healthy (control) and CP children are presented in Table 1A. The children were assigned by the attending physician to a particular level according to the GMFCS. The children at level 1 walked with a velocity higher than the healthy children, whereas children at level 2 and 3 walked much slower. Prior to the official examination, the children were allowed to acquaint themselves with the equipment and the room. The subjects were then weighed, and their body height was measured. The children had only briefs on (room temperature was between 20 and 22 degrees centigrade) during the examination.

2.2. Measurement method

Gait examinations were carried out in the Biomechanics Laboratory of the University School of Physical Education in Wrocław (certificate PN-EN ISO 9001:2009). During the measurements, the children walked barefoot along a straight path. The distance covered by the children was 12 m, which comprised 10 to 12 full gait cycles. This allowed the children to accelerate to the most convenient speed and then to stop safely. Some CP children walked with a gait velocity similar to that selected by healthy children. However, most of them walked more slowly (Table 1A) [15]. Two Kistler force plates built into the walking path registered vertical and two horizontal (anterior–posterior and lateral) components of ground reaction forces as 3D vectors. Children walked along the defined portion of the walking path at least ten times. Some children required more time and more trials to cover this portion in a natural manner, which resulted mainly from locomotor problems and adaptation to the environment. In a few cases, trials were repeated as many as 20 times, and the criterion for the beginning of a correct signal was that it was the first contact with the force plate. For the end of the signal, the toe-off instance of the same limb was used, with the additional requirement that only one foot be on the force plate. At least three correct records of ground reaction forces were registered for the right and left foot.

2.3. Calculation procedure: GRFintegral software

To analyze the ground reaction forces during walking, a special program called GRFintegral was developed. It comprised several procedures:

I. Normalization of components of the ground reaction forces with respect to body weight in CP and healthy children,

II. Normalization of the support time (total support time: 100%),

III. Development of a standard for components of the ground reaction forces in healthy children aged 7,

IV. Semiautomatic division of the standard into 4 parts of the support phase (P1, P2, P3, P4), with the transitions between them being the extrema of the curve defining the norm based on the data from healthy children (Table 1B, Fig. 1A). The lateral component was not divided into parts.

Table 1. Characteristics of CP children participating in the study.
Representative results of the IM evaluation of walking efficiency of child no. 6, together with the results of the children examined, the right (R) and left (L) limb, and the components (x, y, z) and parts of the support phases (P1, P2, P3, P4).

A. Mean age (A), body mass (m), body height (h), walking speed (v), and standard deviation (SD) in healthy and CP (diplegia – 28, hemiplegia – 6) children										
	Controls ($n = 15$)	CP ($n = 34$)	GMFCS I ($n = 5$)	GMFCS II ($n = 20$)	GMFCS III ($n = 9$)					
$W \pm SD$ [years]	7.00 \pm 0.30	11.90 \pm 2.50	12.10 \pm 1.50	12.50 \pm 2.50	10.80 \pm 2.50					
$m \pm SD$ [kg]	25.00 \pm 4.50	36.20 \pm 11.90	41.80 \pm 14.40	35.10 \pm 9.60	38.50 \pm 16.60					
$h \pm SD$ [m]	1.23 \pm 0.05	1.41 \pm 0.17	1.39 \pm 0.20	1.44 \pm 0.14	1.39 \pm 0.23					
$v \pm SD$ [m/s ²]	1.01 \pm 0.13	0.70 \pm 0.29	1.12 \pm 0.18	0.70 \pm 0.15	0.37 \pm 0.13					
B. The IM values divided with respect to stages, from the general (first stage) to the detailed (third stage), for representative children, presented against the background of the GMFCS index										
Child's code	GMFCS	Stage 1			Stage 2		Stage 3			
		IM	IM R	IM L	R x	L x	R y	L y	R z	L z
1	II	1.8	2.0	1.7	2.3	1.5	2.0	2.0	1.8	1.5
2	III	1.9	2.3	1.5	2.5	1.8	2.5	1.8	2.0	1.0
3	III	2.4	2.3	2.4	3.0	3.0	3.0	2.3	1.0	2.0
4	III	2.0	2.3	1.8	2.3	1.0	2.8	2.3	2.0	2.0
5	II	1.7	1.3	2.1	1.5	2.3	1.3	2.0	1.0	2.0
6	II	1.0	1.1	1.0	1.0	0.9	1.0	1.0	1.1	1.2
7	II	1.4	1.5	1.3	1.5	1.5	1.0	1.3	2.0	1.0
8	II	1.7	2.2	1.3	1.8	1.5	1.8	1.3	3.0	1.0
9	II	2.2	2.1	2.3	2.3	2.3	2.0	2.8	2.0	2.0
10	I	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
11	I	1.7	1.4	2.0	1.5	1.5	1.8	1.5	1.0	3.0
C. Example of IM values for child 6 (the most detailed) for Stage 4 evaluation (division with respect to phases)										
Component	R P1	L P1	R P2	L P2	R P3	L P3	R P4	L P4		
x	0.7	1.1	1.2	1.1	1.8	0.7	0.4	0.8		
y	0.7	0.7	0.7	0.9	0.9	0.9	1.8	1.3		
D. Example of IM values for child 6 comprising mean values in five consecutive examinations – progress of therapy – Stage 5										
1	2	3	4	5						
1.3	1.7	1.1	1.3	1						

V. Calculation of the absolute values of instantaneous differences, I_i [no dimension N/D], between the instantaneous value of the component of the ground reaction force for the norm – F_N – and for the CP child – F_{CP} (formula (1), Fig. 1B).

$$I_{s,p,i} = ABS(F_{N_{s,p,i}} - F_{CP_{s,p,i}}), \quad (1)$$

s – limb – left L, right R,
 p – part of the support phase – 1, 2, 3, 4,
 i – ordinal number of a measurement $i = 1, 2, \dots, n$,
 n – total number of measurements.

VI. Summation of the differences (T [N/D]) while retaining a distinction between: left (L) and right (R) limb (s), components of forces (F_x – vertical, F_y – anteroposterior), and parts of support phases (P1, P2, P3, P4) (formula (2), Table 1B).

$$T_{s,p} = \sum_{i=1}^n I_{s,p,i}. \quad (2)$$

2.4. The IM (Integral Classification Scale)

The IM [N/D] is a three-degree scale for assessment of pathological gait with an accuracy of 0.1 based on the components of the ground reaction forces. The calculated maximum Range of the summated differences $T_{s,p}$ (see formula (2)) depends on the parameter analyzed (from 196 for PS on the Y axis to 1289 for TSt on the X axis). The IM value for each parameter was calculated according to equation (3), and the value was rounded to the nearest tenth.

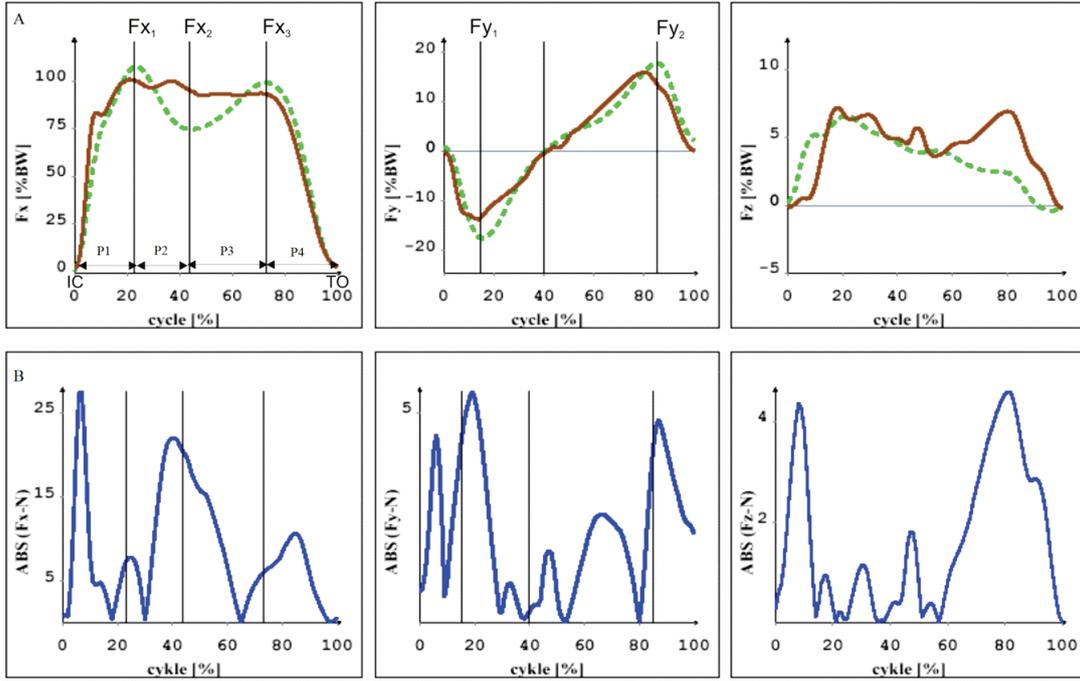


Fig. 1. Representative record of the components of the ground reaction forces in the support phase (total support time: 100%). Parts of support phases P1, P2, P3 and P4. Dashed line N – norm created for healthy children, solid line – record for a CP child, F_x – vertical component, F_y – anteroposterior component, F_z – transverse component, ABS – absolute values of instantaneous differences between the instantaneous value of the component of the ground reaction force for the norm – F_N – and for the CP child – F_{CP} (formula 1), %BW – percent of body weight

$$IM = 3 \frac{T_{s,p}}{\text{Range}}, \quad (3)$$

$T_{s,p}$ [N/D] – summation of the differences,
Range [N/D] – range of the differences.

The best gait efficiency was in children with $IM = 0$, whereas $IM = 3$ was found to be the worst. Value of $0 < IM \leq 1.0$ corresponded to I GMFCS, $1.0 < IM \leq 2.0$ was regarded as II GMFCS, whereas $2.0 < IM \leq 3.0$ was III GMFCS.

The data obtained in healthy children were used only for development of the standard for the components of the ground reaction forces.

3. Results

The examinations that were carried out demonstrated the similarities and differences between the IM and the GMFCS, and an algorithm based on them can objectively support and enhance the GMFCS scale commonly used to assess walking (Table 1). This algorithm has been divided into several stages:

Stage 1, comparison of the mean value of the IM with the GMFCS scale. Pearson's correlation coefficient between the IM and the GMFCS was moderate

($r = 0.610$) and was statistically significant at $p \leq 0.01$.

Stage 2, a division of the IM into parts associated with the right (R) and left (L) limb to assess asymmetry. Verification of the asymmetry coefficient in the examined children was conducted using Student's t -test, which showed statistically significant differences ($p < 0.01$) only in the P3 part of the support phase, which unequivocally points to asymmetry during this phase.

Stage 3, a more detailed analysis of components X, Y and Z. A moderately statistically significant correlation ($0.33 \leq r \leq 0.54$, $p < 0.01$) between the GMFCS and components of the IM. There were no correlations between the GMFCS and the Z component.

Stage 4, comprised of the partial support phases of components P1, P2, P3 and P4. This stage may indicate more or less advanced spasticity in muscles of the lower limbs. A moderately statistically significant correlation ($0.46 \leq r \leq 0.58$, $p < 0.01$) between the GMFCS and the phases of the IM components was found for only a few parameters.

Stage 5, expressed by the general value of the IM (as in Stage 1) or by a more detailed value (as in Stages 2, 3 and 4), can be used to assess the progress of therapy.

As many as 17 in 34 measurements based on the IM during Stage 1 for the CP children showed the same

level as in the case of the GMFCS, 2 children had a higher level, and 15 had a lower level (Table 1B). Pearson's correlation coefficient between the IM and the GMFCS was moderate ($r = 0.61$, $p \leq 0.01$). This confirms the authors' assumption about the usefulness of the IM classification for CP children based on the components of ground reaction forces in walking.

Asymmetry in Stage 2 was found in 11 cases (Table 1B), assuming that the absolute difference was $|IM R - IM L| \geq 0.5$.

Stage 3 is more detailed. The gait is evaluated with consideration of the R and L side and the X, Y and Z components. The IM used in the study involved 106 measurements classified in conformity with the GMFCS (I – 21, II – 69, III – 16), 15 measurements classified as higher levels (I – 9, II – 6) and 89 classified as lower levels (II – 51, III – 38).

The most detailed fourth stage revealed measurements (Table 1C) that indicated higher disturbances in the X and Y components of the P1 part (X component: 8 children, Y component: 6 measurements), P2 (X:8, Y:5), P3 (X:4, Y:6) and P4 (X: 5, Y:21). The values of the IM in other cases were equal or lower than the GMFCS. Table 1C presents the example results of Stage 4 for child No. 13.

Table 1D presents the example results of gait progress during the 2.5-year summer rehabilitation. This constitutes another form of temporal gait analysis as a supplementation of the GMFCS.

4. Discussion

The IM presented in this study has not yet been used in clinical examinations. It might become a valuable supplemental technique for gait analysis, especially for the GMFCS system [10]. The GMFCS scale categorizes CP children from five age intervals (0–2 years, 2–4 years, 4–6 years, 6–12 years) into one of five levels from I to V: the higher the level, the lower a child's motor independence. Levels I–III describe a child who can walk independently or with assistance; levels IV–VI correspond to children moving around in a wheelchair or those carried by other persons. The system is based mainly on a subjective classification concerning motor independence made by physicians or physiotherapists, with particular emphasis on sitting, sitting position (trunk control) and walking.

To interpret components of the ground reaction forces in walking, Herzog et al. [1] defined a parameter called the Symmetry Index (however, they found

that the symmetry was rather indistinct and dependent on the scale used). White et al. [22] applied a coefficient of variability, variance analysis and a coefficient of symmetry in healthy and CP children. Wit and Czaplicki [24] used the ground reaction forces in their solution of the inverse problem of dynamics for walking in disabled persons. White et al. [21] evaluated coefficients of the Fourier series for walking in healthy and CP children. Another method was based on some characteristic points in the ground reaction force patterns [8], [22]. The investigations of ground reaction forces carried out by Seeger et al. [15] demonstrated that the previous positive changes obtained in CP children 18 to 24 months after the completion of treatment were reversed, whereas mean value of the ground reaction forces was reduced.

Analysis of the ground reaction forces in walking uses a variety of methods, which are, however, most often reduced to finding the characteristic points (extremum) of gait patterns and the corresponding time intervals. White et al. [22] report the following relative values of the vertical component of the ground reaction force for children aged 6–11 years: the first peak is 1.25 times the body weight, and the second peak is 1.10 to 1.13 times the body weight. Mann et al. [8] demonstrated that at the age of 5–8 years, the second peak of the vertical component of the ground reaction force is 1.13–1.16 times the body weight, but in some cases, the peak does not attain 100% of the body weight. Therefore, the authors argued that this index cannot be used to assess gait pathology. At the velocity of 1.01 m/s, neither the first nor the second peak (Fx1 and Fx3) are observed in the vertical component in children with hemiplegia and contractures of muscles spanning the ankle joint together with abnormal foot planting, resulting in only one maximum value of the ground reaction force at the middle stance instead of peaks 1 and 2 [2]. Similar characteristics of the ground reaction forces were found in the present study. Healthy children demonstrated typical patterns for the ground reaction forces with all peaks discussed in the literature. In contrast, the CP children had reduced values of GRF at the peaks or there were no peaks. However, the data concerning the characteristic points are insufficient to assess the level of the disorder and the effects of rehabilitation. This is quite important because even in healthy children, the peak heights depend upon the age of a child [3], its body height [1], [17], and its walking velocity [14], [16].

Using other methods for interpretation of the components of ground reaction forces is also of little practical significance in CP children. Examination of asymmetry by using the Symmetry Index [7] was not

sensitive enough, and according to those authors, depended on the scale used. Other methods of gait assessment, such as the coefficient of variability, analysis of variation [22] and harmonic analysis of the ground reaction forces [21], have not been accepted for the functional classification of CP children, either. Therefore, it seems useful to apply the IM procedure presented in this study to supplement the GMFCS-based assessment of motor abilities in CP children. This procedure is simple and feasible even in doctor's offices in which a system for 3D movement analysis cannot be used. In the case of the IM, it is sufficient to use a small platform and software.

Data from one child obtained over the period of a 2.5-year-long rehabilitation program have been deliberately included in this study (see Table 1D) to illustrate the potential of the proposed method, which makes it possible to monitor, with an accuracy of 0.1 degree, the development of asymmetry and the progress of gait efficiency in terms of 3 components and the 4 parts of the support phases (P1, P2, P3 and P4). According to Perry [11] and Gage [6], the information on muscles that are active in the consecutive phases of a gait cycle together with a synchronous account of the components of the ground reaction forces may help the physiotherapists and physicians indicate the ways to make the gait pattern of a CP child approach the norm.

It was also deliberate in the present study to present the mean data of CP children in the process of rehabilitation to justify the use of the IM to supplement the GMFCS functional classification of CP children within its narrow range. Slightly lower IM levels compared with GMFCS levels in some children might suggest that the gait is more efficient or is improving and that a child might soon progress to a lower level.

Our research has shown that the IM can be used to supplement the GMFCS method. The results of the correlations described in the Results section indicate that the dependence of the IM and the GMFCS is moderate. This suggests that the two methods are supplementary, and not redundant, and the addition of the IM to the GMFCS could be beneficial.

This method of data interpretation provides information that is more useful than that based solely on selected extreme points. The IM of analyzing the components of the ground reaction forces generated during walking in CP children can be used in clinical gait assessment to determine the differences between pathological and normal gait, not only in children but also in adults, e.g., patients after cerebral hemorrhage and cerebral injuries; bone fractures in lower limbs; and injuries of the ankle, knee and hip joints. It can be used both before and after treatment.

However, prior to its introduction, specific detailed guidelines and standards must be developed to determine the limits of the scale for each component of the ground reaction forces. This might help differentiate gait characteristics between healthy and CP children or between various subgroups within the CP group. However, it should be noted that the data from any equipment in gait analysis might be used only if accompanied by a complete medical examination.

5. Conclusions

The analysis of ground reaction forces during walking in CP children demonstrated similarities and differences between the IM and GMFCS methods. Taking into account the complexity and comprehensiveness of the GMFCS method, it was found that the IM has several important characteristics that could enhance the GMFCS classification:

1. Objective and quantitative assessment of motor abilities,
2. Detection of asymmetry,
3. Assessment of foot support technique and correctness of muscle activity patterns for a particular force component and part of the support phase (P1, P2, P3 and P4),
4. Diagnosis of the improvement of the gait pattern,
5. Simple and fast diagnosis technique for pediatricians, neurologists, orthopedists, surgeons and physiotherapists without the need to acquire technical knowledge,
6. Innovative method of diagnosing gait disorders that extends the range of disorders that can be treated, e.g., disorders caused by cerebral hemorrhage and cerebral injuries; bone fractures in the lower limbs; and injuries of the ankle, knee and hip joints. Therefore, it opens up opportunities to encourage 'healthy aging' of the society.

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