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INFLUENCE OF ANKLE-FOOT ORTHOSES ON GAIT SYMMETRY IN CHILDREN WITH HEMIPLEGIC CEREBRAL PALSY: a prospective, cross-sectional study

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Abstract

Purpose: The main objective of study was to analyse gait kinematics in terms of symmetry among groups of children with hemiplegic cerebral palsy (CP).

Material and methods: The study was conducted using the BTS SMART three-dimensional (3D) gait analysis optoelectronic system. Passive reflective markers were placed on subjects' bodies in accordance with the Davis protocol. The study involved 43 children, aged seven years. Group 1 (n=18) comprised patients not using any orthopaedic equipment. Group 2 (n=14) consisted of children using a unilateral ankle-foot orthosis on the affected side. Group 3 (n=11) included children using bilateral ankle-foot orthoses.

Results: Improvement in gait symmetry was observed in orthosed children, and the majority of changes were significant (p<0.05). Thus, it appears that this type of orthopaedic equipment affects not only the ankle joint, but also higher levels of the biokinematic chain.

Conclusions: In accordance with the results, it was shown that in patients using bilateral ankle-foot orthoses, a more positive effect of the described phenomena could be expected.

Keywords: cerebral palsy – hemiplegia – gait – symmetry – ankle-foot orthoses

INTRODUCTION

Cerebral palsy (CP) is a prevalent neurodevelopmental condition that originates in early childhood and persists throughout the lifespan [5]. This is a term commonly used to describe a variety of motor conditions associated with brain damage. When diagnosed in patients with cerebral palsy, it causes a delay in the development of neurological mechanisms controlling posture, balance and movement [50,54]. Additionally, the muscles responsible for properly performing these activities are usually characterised by low efficacy, most frequently being the consequence of their spasticity.

It is estimated that the incidence of cerebral palsy is 2-3‰ in the population, while hemiplegia - which can be congenital or acquired - is one of its most common forms (above 38%) [27]. Typical symptoms include paresis, affecting the upper and lower limbs on one side of the body. This condition results in trunk and limb asymmetry, alongside postural instability, which collectively impair gait patterns - in this case—leading to pathological locomotion. [24]. Children with hemiplegic cerebral palsy exhibit a longer gait cycle and support phase relative to the swing phase, alongside a slower walking speed compared to their healthy peers. Significant differences occur in hip, knee and ankle joint angles between children with cerebral palsy and their healthy peers at the moment of touching the ground and buffering, as well as during pedal extension [55]. At the same time, patients with hemiplegia demonstrate very high motor functioning - according to the Gross Motor Function Classification System (GMFCS) scale - they are classified at the 1st or 2nd level of locomotion, which proves that these are children who perform movement independently and actively participate in social life [12].

Orthotic treatment offers the possibility of remedying many conditions that affect gait and body posture, acting as an element supporting and extending the effects achieved during exercise. In patients with hemiplegia, individually fitted, solid ankle-foot orthoses are most frequently used [55]. By maintaining the ankle joint in an intermediate position, they can improve gait quality [21].

According to the current guidelines of the World Health Organization and the functional rehabilitation model (International Classification of Functioning, Disability and Health), therapy is aimed at achieving the greatest possible independence of the patient. In children with hemiplegia, due to their high independence, the use of ankle-foot orthoses is not aimed at learning to walk, but only at improving gait quality. It has been proven that their use increases step length and reduces flexion of the limb in the knee joint during heel contact with the ground [6]. Beneficial changes in kinetic and kinematic gait indices [52], as well as improved trunk stability during locomotion [48], have also been reported. Consequently, in a systematic review of the literature, the positive effect of ankle-foot orthoses use on gait pattern was confirmed in children with cerebral palsy, including reference to its subtype - hemiplegia [33,41]. It is widely established that the application of ankle-foot orthoses (AFOs) has a positive impact on spatiotemporal parameters of gait, such as cadence and velocity. Furthermore, AFOs demonstrate positive effects on ankle, knee and hip kinematics as outcomes in straight line walking and stair ascent/ descent, as well as the performance of specific reach-related tasks. Although the oldest and the newest studies mentioned here are separated by a considerable time interval, some of the conclusions are still valid and consistent to date. Both Miccinilli et al. and Ridgewell et al. [33,44] emphasize that ensuring homogeneity of gait pattern in a subject sample is of significance, and that further research employing less heterogeneous types of orthoses and at a lower risk of bias are still necessary to reach conclusions concerning the actual effectiveness of orthosis use. The above-mentioned comments contributed to undertaking the present research aimed at assessing the symmetry of gait among children with hemiplegic cerebral palsy.

Until recently - in physiotherapy practice - lower limb orthoses were used in children with hemiplegic cerebral palsy, but only on the affected side. Delgado et al. [10] indicated that despite damage to one side of the body, the other - seemingly healthy is not functioning to its fullest potential, and therefore, it also requires orthopaedic care. Thus, the above-mentioned authors used botulinum toxin injections for the muscles of one or both lower limbs. This is possibly one of the reasons why physiotherapists are currently more frequently recommend the use of orthoses for both lower limbs. Such action can provide the patient with a sense of body symmetry, which is important in shaping correct movement patterns [51]. However, the mentioned observations are still awaiting scientific verification. The present available literature contains conclusions that may constitute grounds for changing the orthopaedic management of children with hemiplegic CP. It is desirable to strive for movements (cyclical and acyclic) requiring the involvement of the left and right sides of the body that are characterised by the greatest possible similarity (symmetry). Although locomotion problems are among those most frequently described in the literature, deficiencies in this area are not only restricted to gait but affect all aspects of [25,56]. Elnaggar [14] linked the level of asymmetry in gait with the processes of maintaining dynamic balance. Assuming that their control is similar, attention to the quality of performing even the simplest tasks may effectively influence symmetrisation in children with hemiplegic CP. In our previous research [49], it was shown that the use of two orthoses had a positive effect on body stability in a static posture. It is possible that the use of bilateral AFOs may also demonstrate beneficial outcomes in the case of more complex motor activities.

Additional evidence is provided by the mechanical analysis of locomotor movements among children with hemiplegic CP. Undoubtedly, ensuring movement symmetry (especially including gait) using a unilateral ankle-foot orthosis is more difficult than applying orthoses bilaterally, especially in conditions of reduced lower limb muscle strength on the affected side (taking the effect of spasticity into account). It can be inferred that in children under the age of 10, who typically possess lower body mass, the use of orthoses significantly increases the shifted mass of the segment (lower limb orthoses). This additional mass inherently predisposes the patient to locomotor asymmetries. It seems that a prerequisite for ensuring symmetry of locomotion may be relative equalisation regarding the mass of each lower limb (including the ankle-foot orthosis).

This leads to an attempt to determine whether the use of bilateral orthoses in patients with hemiplegic cerebral palsy provides greater benefits for gait symmetrisation than the use of only a unilateral orthosis. Such determination seems to be possible only through technological advances and the use of optoelectronic gait analysis systems in gait studies of children with hemiplegic CP. Analysis of older [38] and newer literature [43] proves to be a promising direction of research.

Study aim

The main objective of this study was to analyse gait kinematics in terms of their symmetry among groups of children with hemiplegic cerebral palsy performing gait without orthoses, and with unilateral or bilateral ankle-foot orthoses. The following research questions were formulated:

1. Do ankle-foot orthoses have a positive effect on the symmetrisation of lower limb locomotor movements performed by children with hemiplegic cerebral palsy?
2. Does the type of orthopaedic equipment (unilateral vs. bilateral) affect the value of kinematic gait indices?
3. Does the degree of gait symmetry in children with hemiplegic cerebral palsy depend on the type of orthopaedic equipment used (uni- vs. bilateral ankle-foot orthoses)?

MATERIALS AND METHODS

This prospective, cross-sectional study was conducted at the University of Physical Culture in Kraków, in strict adherence to the ethical principles outlined in the 1964 Declaration of Helsinki. The research protocol was approved by the Bioethics Committee of OIL in Kraków (74/KBL/OIL/2015). The study was conducted in a certified laboratory (PN-EN ISO 9001), the dimensions of which were 15 m x 8 m x 3 m (length, width and height, respectively). The volume of the measurement space was approximately 140 m^3 (8 m × 8 m × 2.2 m). All research participants and their legal guardians were familiarised with information regarding the purpose and course of the research, they signed a declaration of conscious and voluntary participation in the research project and were informed about the possibility of withdrawing from participation in the study at any stage, without providing justification. The research procedures, developed research methodology and measurement tools had no impact on the current health status of the children under study.

Subject characteristics

The study involved 43 children - selected via convenience sampling - who regularly (twice a week) attended individual physiotherapy sessions at the Family Medical Centre in Skawina (Poland), where the co-author of this paper is currently employed. All children participating in the programme were diagnosed with hemiplegic CP. In each case, the diagnosis was confirmed by a neurologist based on tests (including magnetic resonance imaging), in accordance with the requirements of ICD 10 (International Statistical Classification of Diseases and Related Health Problems). Children diagnosed with hemiplegic CP were qualified for participation in this research programme based on a certificate issued by a physician specialising in motor rehabilitation.

The main inclusion criteria for the study were:

• diagnosis of cerebral palsy in the form of hemiplegia;

• spastic unilateral subtype of cerebral palsy;

• qualification to the 1st or 2nd level characterising the quality of locomotion according to the GMFCS classification;

• age between five and ten;

• confirmation of so-called intellectual norm, an essential feature for efficient verbal communication between research participants;

• in Groups 2 or 3, use of solid ankle-foot orthoses for no less than three months;

• no medical contraindications to comprehensive physiotherapy.

The exclusion criteria comprised:

• double hemiplegia or other disorders not diagnosed as hemiplegic CP;

• mechanical musculoskeletal injuries within 12 months preceding examination;

• lack of consent to continue the research procedure.

Three groups were selected:

• Group 1 (n=18, including 12 boys) - hemiplegic children who, on a daily basis, do not use any orthopaedic equipment for the lower limbs;

• Group 2 (n=14, including six boys) - hemiplegic children who, on a daily basis, use unilateral ankle-foot orthoses on the affected side;

• Group 3 (n=11, including five boys) - hemiplegic children who, on a daily basis, use bilateral ankle-foot orthoses.

Participants in Groups 2 and 3 consisted exclusively of children for whom solid AFOs had been recommended by a specialist. The same physician, based on the clinical image and the examination results, decided on the number of solid orthoses to be applied to the patient (unilateral or bilateral). These orthoses had a full plantar plate adjusted to reach the toes. This prompted the use of the Davis protocol in the study, which ignored mobility in the metatarsophalangeal joints (omitting the third rocker). These considerations determined the availability of the study patients and formed the basis for the unequal patient division in the individual groups.

In this study, we intentionally decided not to conduct measurements in a peer (control) group as they were unrelated to the study's objectives. Furthermore, such comparisons would have significant limitations. Chronological (calendar) age is not an appropriate criterion for comparison due to the developmental delay in children with hemiplegic CP [47]. The lack of a control group is not uncommon, as evidenced by the data presented in [14]. It should be assumed that the neurological diversity of the participants could influence the biomechanical image of gait, particularly in children during the developmental period. Analysis of the relevant literature demonstrates significant variability in temporal and spatial gait parameters in hemiplegic CP [35,43,46].

The basic descriptive characteristics of the respondents are presented in Table 1.

Table 1. Patient demographics

	Group 1	**Group 2**	**Group 3**
	M±SD	M±SD	M±SD
Age [years]	7.5±1.7	7.4±1.9	7.2±1.9
Body height [m]	1.19±0.1	1.24±0.12	1.21±0.12
Body mass [kg]	23.8±5.7	26.6±6.3	25±6.2

Research procedures

The most important component of the measurement stand was the BTS SMART D-140 6 TVC optoelectronic system (BTS Bioengineering, Garbagnate Milanese, Italy). Before beginning the video recording, mandatory anthropometric measurements were taken for each patient. In the case of each measurement, they were performed by the same trained person with appropriate anatomical knowledge. In this part of the study, a certified medical scale with a height gauge (model WGILAB-RDW-391, Poland), Martin's bow callipers and a certified tape measure (in centimetres) were used (GPM, Switzerland). According to the assumptions of the Davis protocol, the following were determined [9]:

- pelvic width (between anterior superior iliac spines) [mm];
- pelvic depth (shortest distance between anterior superior iliac spine and long axis of the femur at level of greater trochanter) [mm];
- knee width (between femoral condyles) [mm];
- ankle width (between lateral and medial malleolus) [mm];
- total length of the thigh and shank (from trochanter's upper edge of greater femur to lateral malleolus) [cm].

This part of the research procedure was similar to that presented in [13].

Body height and mass measurements were carried out in a standing position, while all other measurements were taken in supine position on a medical couch. The elements of the research procedure mentioned above gave rise to the later use of original models and algorithms created by the designers of the BTS System.

After conducting anthropometric measurements, spherical passive markers were attached to the anatomical landmarks using double-sided adhesive tape. This was done in accordance with the Davis protocol (dedicated to subjects aged five to ten).

Then, in the designated measurement space, 12 transitions (different gait variants) were recorded each time, with at least six full cycles. Thus:

- patients from Group 1 (without orthoses) performed gait without orthopaedic support (so-called "basic gait variant");

• patients from Group 2 (unilateral orthosis) performed the basic gait variant without AFOs and then with a unilateral ankle-foot orthosis on the affected side;

• patients from Group 3 (bilateral orthoses) performed the basic variant without AFOs and then with bilateral ankle-foot orthoses.

The examined children performed the basic gait variant while walking barefoot. In turn, during gait carried out in orthoses, the patients wore their own orthopaedically fitted shoes, with appropriately glued soles, considering (for individual cases) the uneven length of the lower limbs. The need to consider the applied orthopaedic equipment was the reason why the markers placed in the area of the lower leg (shank), ankle joint and foot were moved to the arms of the orthosis and footwear. The alteration in walking conditions required adjustments to the lower limb anthropometric parameters measured, both above and below the ankle joint, to account for the new circumstances

When processing the measurement data, it was assumed that one gait cycle begins with the foot placing on the ground (initial contact) and ends with the next time the same foot is placed on the ground. Within this cycle, two phases were distinguished: contact with the ground (stance phase) and swing phase, separated by the moment the foot leaves the ground. For each gait cycle, the subjects walked at a speed considered most comfortable and individually selected by them. The mean values of the following variables characterising the gait of children with hemiplegic cerebral palsy (with and without ankle-foot orthoses) were determined:

• gait speed, width and frequency of steps;

• range of motion in the ankle, knee, hip and pelvic joints during the gait cycle and its phases (sagittal plane).

For the angular variables mentioned above, it was decided to report ranges of motion within the gait cycle and individual phases. This approach enables a more detailed analysis of the motor deficits in children with hemiplegic CP, facilitating their potential classification in alignment with current clinical trends [35,53]. Previous studies have relied on instantaneous angular values recorded at characteristic nodal points. Analysis of such data demonstrates significant variability [46], as evidenced by the high values of the calculated coefficients of variation. The method proposed in this study for representing angular changes in joints during gait also appears to better characterise the movement capabilities of the kinematic chain formed by the lower limb, both when the chain is open (swing phase) and closed (stance phase).

As mentioned, this study was focused on the phenomenon of symmetry in lower limb and pelvic movements during gait performance in children with hemiplegia (CP). This issue has been previously described in many studies. Various numerical indices were used to quantitatively assess differences in movement between the affected and unaffected sides of the body [7,11,14]. Analysis of this literature shows that absolute descriptions of observed differences are usually more sensitive and provide more detailed information than those based on proprietary mathematical formulas. Therefore, in our study, we decided to compare the absolute values of variables recorded on the affected and unaffected sides. This approach is also supported by the fact that the sagittal plane divides the human body into two symmetrical halves - the left and right. Statistical tools were used to compare the differences observed between them. The approach is further grounded in the description given by Herzog et al. [23], defining symmetry as perfect agreement between external kinematics of the left and right limbs and used in research on symmetry during locomotion [16]. As can be noted, specific motion symmetry indices were not used in this study. On the one hand, such a situation may make the comparison of our results to those obtained by other authors difficult. On the other, to the best of our knowledge, the measurement data presented here allow for their application to various specific symmetry indices. Of course, this may constitute a limitation of our research, as discussed in the relevant section of the text.

Due to the fact that the children were dressed only in underwear during testing, the laboratory was air-conditioned, ensuring an appropriate, constant ambient temperature and air humidity to guarantee thermal comfort of the participants.

Statistical analysis of the results

Statistical analysis was performed using the IBM SPSS Statistics 26 statistical package. The following measures were used to describe the collected quantitative data: arithmetic mean (M) and standard deviation (SD). The Shapiro-Wilk test was used in the statistical analysis to test the assumption of distribution normality with regard to the results. One-way ANOVA was applied to evaluate differences between the studied groups. In turn, to test the differences between the affected and unaffected sides and determine whether they varied significantly between the groups, two-way MANOVA was implemented.

In order to establish the effect strength, partial eta squared (η^2_P) was calculated, the values of which (>0.01, 0.06 and 0.14) correspond to its small, medium and large levels [8].

In the case of significant interactions, the probability for post-hoc assessments was calculated using the Bonferroni post-hoc test [19].

Effects, for which the probability p value was less than the adopted significance level of $\alpha=0.05$ ($p<0.05$), were considered significant in all of the analyses.

Although a number of statistical tests were used in the analyse, the small sample sizes may pose a potential risk of the test results being falsely positive. This observation should be considered a limitation of the study.

RESULTS

The kinematic characteristics of gait are presented in Table 2. The results of ANOVA did not indicate statistically significant differences between the studied groups of hemiplegic children, regardless of whether ankle-foot orthoses were worn.

With regard to comparison of the measured parameters between the orthosed and non-orthosed conditions, significant differences were noted in average gait speed ($F(1, 23)=6.178$; $\eta^2_P=0.212$; $p=0.021$) and step width ($F(1, 23)=6.178$; $\eta^2_P=0.212$; $p=0.021$). Higher values of the above given variables were noted in the gait performed with orthoses.

Table 2. Gait speed, width and frequency of steps in the studied groups of children

Orthosis	Group 1	Group 2	Group 3
	Gait speed [m/s]		
	M±SD	M±SD	M±SD
No	0.96±0.22	**0.90**$^{\&}$±0.23	**0.85**$^{\&}$±0.24
Yes	-	**0.97**±0.24	**0.96**±0.25
	Step width [m]		
	M±SD	M±SD	M±SD
No	0.16±0.03	**0.16**$^{\&}$±0.02	**0.16**$^{\&}$±0.02
Yes	-	**0.17**±0.03	**0.18**±0.03
	Step frequency [steps/min]		
	M±SD	M±SD	M±SD
No	116±13	120±18	119±18
Yes	-	113±11	114±11

$^{\&}$ - without vs. with orthoses, $p<0.05$

In the ankle joints (Table 3), no significant differences were indicated between the affected and unaffected sides when the children did not wear orthoses (p>0.05). However, differences were observed between the sides of the body when the children (Groups 2 and 3) wore them. These differences concerned range of motion in the ankle joint during the gait cycle ($F(1, 23)=25.842$; $\eta^2_P=0.529$; $p<0.001$) and swing phase ($F(1, 23)=21.925$; $\eta^2_P=0.488$; $p<0.001$). In the case of the stance phase, a trend of differences was noted ($F(1, 23)=3.912$; $\eta^2_P=0.145$; $p=0.060$). Furthermore, statistically significant interactions were indicated: Side [unaffected vs. affected] × Group [1 vs. 2 vs. 3] concerning range of motion when wearing the orthoses during the gait cycle ($F(1, 23)=12.111$; $\eta^2_P=0.345$; $p<0.001$) and in the swing phase ($F(1, 23)=12.310$; $\eta^2_P=0.349$; $p=0.002$). In these conditions, Group 2 (unilateral AFOs) exhibited a significantly greater difference regarding range of motion compared to Group 3, comprising children with bilateral orthotic support.

Table 3. Characteristics of range of motion in ankle joint during gait cycle and its phases (sagittal plane)

Orthosis	**Group 1**		**Group 2**		**Group 3**	
	Affected s.	Unaffected s.	Affected s.	Unaffected s.	Affected s.	Unaffected s.
Range of motion during gait cycle [°]						
No	29.49±7.22	28.14±3.75	27.31±6.48	28.04±3.99	26.35±5.82	28.25±3.78
Yes	-	-	**21.23***±4.35	**32.98**$^{\#}$±5.40	**20.98***±4.41	**23.18***±5.72
Range of motion during stance phase [°]						
No	23.74±6.06	22.63±5.19	**21.48**$^{\&}$±8.00	23.78±5.65	**20.05**$^{\&}$±6.07	22.28±5.09

Yes	-	-	**18.40***±3.85	22.87±7.57	**17.94***±4.77	19.49±4.45
Range of motion during swing phase [°]						
No	13.51±7.76	17.91±4.21	14.71±6.53	15.43±5.19	14.92±8.11	16.04±7.72
Yes	-	-	**10.91***±5.98	**24.59**#±5.47	**10.23***±5.79	**12.29**±4.54

* - affected vs. unaffected side $p<0.05$

\# - Group 2 vs. Group 3, $p<0.05$

& - without vs. with orthoses, $p<0.05$

With regard to range of motion in the knee joint (Table 4), both for the gait cycle and its phases, no differences were observed between the examined groups ($p>0.05$).

The results of MANOVA demonstrated significant differences in knee joint mobility during the swing phase when the children from Groups 2 and 3 used ($F(1, 23)=10.993$; $\eta^2_P=0.323$; $p=0.003$) or did not use ankle-foot orthoses ($F(1, 40)=11.857$; $\eta^2_P=0.229$; $p=0.001$). In both cases, the values were lower on the affected side. Statistical analysis indicated a trend for the Side [unaffected vs. affected] × Group [1 vs. 2 vs. 3] interaction. This concerned the range of motion in the gait cycle when the children wore orthoses ($F(1, 23)=3.627$; $\eta^2_P=0.136$; $p=0.069$) - a significantly smaller difference between the sides was observed in children who used bilateral orthoses (Group 3).

In the case of the results obtained for MANOVA, regarding differences between the recorded ranges of motion in the knee joint when children did not wear orthoses compared to when they wore them, such variances were indicated in: range of motion during the gait cycle on the affected ($F(1, 23)=10.658$; $\eta^2_P=0.317$; $p=0.003$) and unaffected side ($F(1, 23)=41.530$; $\eta^2_P=0.644$; $p<0.001$), and range of motion during the swing phase on the affected ($F(1, 23)=6.452$; $\eta^2_P=0.219$; $p=0.018$) and unaffected side ($F(1, 23)=37.720$; $\eta^2_P=0.621$;

p<0.001). Each time, greater ranges of motion were noted during gait performed using ankle-foot orthoses.

Table 4. Characteristics of range of motion in the knee joint during gait cycle and its phases (sagittal plane)

Orthosis	**Group 1**		**Group 2**		**Group 3**	
	Affected s.	Unaffected s.	Affected s.	Unaffected s.	Affected s.	Unaffected s.
Range of motion during gait cycle [°]						
No	52.58±11.79	50.98±7.18	**49.38**$^{\&}$±11.39	**55.84**$^{\&}$±7.82	**52.26**$^{\&}$±13.60	**54.28**$^{\&}$±7.12
Yes	-	-	**53.30**±12.49	**60.64**±3.85	**58.81**±13.40	**62.49**±4.43
Range of motion during stance phase [°]						
No	28.52±11.06	26.96±10.06	25.53±9.74	34.97±15.13	27.06±16.63	32.59±14.16
Yes	-	-	26.97±7.96	29.62±7.41	29.67±11.62	31.17±7.71
Range of motion during swing phase [°]						
No	**45.28***±10.89	**46.61**±6.93	**39.58**$^{*\&}$±10.59	**49.72**$^{\&}$±4.95	**43.17**$^{*\&}$±11.51	**49.15**$^{\&}$±7.69
Yes	-	-	**43.59***±16.43	**56.01**±5.33	**49.45***±15.16	**56.12**±4.67

* - affected vs. unaffected side, *p*<0.05

$^{\&}$ - without vs. with orthoses *p*<0.05

The results regarding range of motion in the hip joint during gait performed by children with hemiplegic cerebral palsy are presented in Table 5. ANOVA allowed to indicate significant differences between the groups in the gait cycle on the unaffected side

(F(2, 42)=3.528; p=0.039). The post hoc test only demonstrated significant differences between Groups 1 and 2, in which higher values were noted. Significant differences were also observed between the sides of the body (affected and unaffected) during gait performed without ankle-foot orthoses (F(1, 40)=18.180; η^2_P=0.441; p<0.001). The analysis also proved a trend of differences when the children wore the ankle-foot orthoses (F(1, 23)=3.685; η^2_P=0.138; p=0.067), and higher values were seen on the unaffected side. Comparable trends were observed for range of motion during the stance phase, both in orthosed(F(2, 40)=27.597; η^2_P=0.285; p<0.001) and non-orthosed conditions (F(1, 23) =21.514; η^2_P=0.483; p<0.001). Furthermore, significant effects were noted in the swing phase of gait while utilising orthoses (F(1, 23)=6.008; η^2_P=0.207; p=0.022).

MANOVA, applied for the assessment of differences in indices characterising movement in the hip joint during gait performed with and without ankle-foot orthoses, revealed significantly higher ranges of motion in the discussed joint among children using orthoses. This was the case for: the gait cycle on the affected (F(1, 23)=6.144; η^2_P= 0.211; p=0.021) and unaffected side (F(1, 23)=12.295; η^2_P=0.348; p=0.002), the stance phase on the affected (F(1, 23)=14.912; η^2_P=0.393; p=0.001) and unaffected side (F(1, 23)=7.629; η^2_P=0.249; p=0.011), and the swing phase also on the affected (F(1, 23)=18.372; η^2_P=0.444; p<0.001) and unaffected side (F(1, 23)=17.989; η^2_P=0.439; p<0.001).

Table 5. Characteristics of range of motion in hip joint during gait cycle and its phases (sagittal plane)

Orthosis	**Group 1**		**Group 2**		**Group 3**	
	Affected s.	Unaffected s.	Affected s.	Unaffected s.	Affected s.	Unaffected s.
Range of motion during gait cycle [°]						

No	**45.12***±8.27	**47.88**$^{\#}$±7.70	**45.66**$^{*\&}$±8.02	**54.96**$^{\&}$±7.71	**46.27**$^{*\&}$±7.73	**50.48**$^{\&}$±6.83
Yes	-	-	**48.43**±6.95	**57.13**±6.86	**49.96**±6.13	**56.60**±7.41
Range of motion during stance phase [°]						
No	**36.37***±6.81	**46.46**±7.97	**39.84**$^{*\&}$±8.72	**52.76**$^{\&}$±9.25	**41.53**$^{*\&}$±7.87	**47.97**$^{\&}$±8.72
Yes	-	-	**44.09***±8.40	**54.32**±9.01	**47.43***±6.13	**54.37**±8.79
Range of motion during swing phase [°]						
No	33.96±7.95	37.97±8.83	**36.96**$^{\&}$±6.37	**36.64**$^{\&}$±12.20	**37.85**$^{\&}$±7.86	**34.19**$^{\&}$±13.60
Yes	-	-	**42.62**±6.29	**47.38**±6.78	**43.47**±6.43	**47.65**±7.10

$^{\#}$ - Group 1 vs. Group 2, *p*<0.05

* - affected vs. unaffected side, *p*<0.05

$^{\&}$ - without vs. with orthoses, *p*<0.05

Descriptive statistics of pelvic movement in the sagittal plane of children with hemiplegic cerebral palsy are presented in Table 6. One-way ANOVA did not indicate significant differences between groups in any of the described indices (*p*>0.05). However, significant differences were observed in the range of pelvic movement during the swing phase when the children did not wear orthoses (F(2, 40)=13.368; η^2_P=0.250; *p*=0.001), and they were greater on the affected side. When the children wore orthoses, no such differences were observed (*p*>0.05). For analysis of the interaction side [Unaffected vs. Affected] × Group [1 vs. 2 vs. 3], significant interactions were observed only in the swing phase during gait performed with orthoses (F(1, 23)=4.564; η^2_P=0.166; *p*=0.044), and children wearing a unilateral ankle-foot orthosis (Group 2) exhibited greater ranges of motion on the affected side, whereas children who wore bilateral ankle-foot orthoses (Group 3) demonstrated larger ranges of motion on the unaffected side.

Table 6. Characteristics of pelvic range of motion in gait cycle and its phases (sagittal plane)

Orthosis	Group 1		Group 2		Group 3	
	Affected s.	Unaffected s.	Affected s.	Unaffected s.	Affected s.	Unaffected s.
Range of motion during gait cycle [°]						
No	7.35±3.26	7.27±3.21	7.83±2.86	7.89±2.86	6.75±2.60	6.85±2.36
Yes	-	-	8.58±3.38	8.42±3.17	7.17±3.03	7.13±3.17
Range of motion during stance phase [°]						
No	6.37±3.34	6.71±3.46	6.91±2.67	7.43±3.27	6.16±2.59	6.28±2.81
Yes	-	-	7.29±3.06	7.39±3.76	6.73±2.99	6.50±3.59
Range of motion during swing phase [°]						
No	**6.05***±3.83	**4.23**±2.22	**6.48***±3.93	**3.47**$^{\&}$±1.49	**4.61***±3.35	**3.55**$^{\&}$±1.67
Yes	-	-	6.51±4.47	**5.16**±2.77	4.55±4.35	**5.93**±2.80

* - affected vs. unaffected side, $p<0.05$

$^{\&}$ - without vs. with orthoses, $p<0.05$

DISCUSSION

Cerebral palsy is the most common physical disability in childhood. Therefore, discoveries are still being made regarding the early diagnosis, prevention and treatment of CP. This affects, among others, prognosis and treatment options for such patients. A total of 182 interventions were identified aimed at minimising the symptoms of hemiplegic cerebral palsy [37]. Among them, 23% were aimed at prevention, and 77% at controlling its effects. In the latter category, health, pharmacological, surgical, regenerative and complementary as well as alternative medicine interventions were distinguished. In this study, an intervention related to the use of orthoses was implemented. It was proven that the use of orthopaedic equipment in combination with, for example, resistance exercises, provides positive results [37]. Such protocols allow to reduce muscle strength deficits on the affected side of the body [18] as well as asymmetries in gait, and the energy cost of gait also experiences a reduction [3,15]. Therefore, lower limb orthoses are currently one of the pillars in the treatment of cerebral palsy [1,42].

As earlier stated, one of the main goals of improving the mobility of patients with hemiplegic CP during locomotion is to achieve symmetrisation. This results in improving the patient's daily functionality, for example, by making it easier to overcome architectural barriers. Thus, in the present study, it was decided to compare biomechanical gait indicators recorded for the affected and unaffected sides of the body in order to assess symmetry in dynamic conditions, depending on the type (unilateral vs. bilateral ankle-foot orthoses) of orthopaedic equipment used.

The results of the current research indicated the mechanical impact of AFOs on proximal levels of the biokinematic chain in the lower limb, both when it is closed (e.g. standing position or stance phase during gait) and open (e.g. swing phase). Similar opinions have been reported earlier [29,40], but in this study, these relationships were described considering the type of AFOs used (unilateral vs. bilateral).

In patients from Groups 2 and 3, the assessment of kinematic gait indices showed a significant increase in speed after putting on the ankle-foot orthoses. This type of observation is supported by a review of literature [1,26]. The obtained results also exhibited that the average speed values did not exceed 1 m/s, or differ significantly between the groups. The aforementioned literature allowed to note that the levels were within the normative range. The results achieved in this area did not change significantly - this is probably due to patients with hemiplegic cerebral palsy constituting a group that exhibits very high motor functioning, especially in conditions of gait performed at a free and safe speed. It is worth mentioning, however, that multi-tasking performed by children with hemiplegia can reduce the speed of gait as well as the length and frequency of steps.

Therefore, during this type of examination, attention should be paid to the conditions in the research room, such as: the number of people and verbal commands, as well as acoustic stimuli.

In the present trial, a tendency was revealed towards an increase in the length of steps, but only in Group 3 after the patients put on the bilateral orthoses. A trend towards equalizing steps on the affected and unaffected sides was also found, which indicates a shift towards gait symmetrisation. Such observations were supported, among others, in the research conducted by Hayek et al. [22], who analysed the gait of 18 patients with hemiplegic cerebral palsy. They reported that after applying the AFOs, the step length increased by 11.7%. This may be an argument for using bilateral orthoses in clinical practice among patients with hemiplegic cerebral palsy. In this study, it was shown that in the groups of orthosed children, in addition to the increase in the length of steps, their width also experienced a significant increase (on average, from one to two cm). This phenomenon may potentially be associated with increased locomotion safety, making gait less susceptible to the negative effects of mechanical interference. Of course, it cannot be ruled out that the wider step width may have been influenced by the design of the orthosis and the patient's footwear [32], as well as by the reduced centre of gravity deflection in neurological patients using orthoses [28].

Ankle-foot orthoses provide maximum protection for the ankle joint but, at the same time, limit its dorsal and plantar flexion during gait [2]. Such an observation was confirmed in the current study. The limitation of mobility (in Group 2) on the affected side was, on average, six degrees. In turn, when the patients were equipped with bilateral orthoses (Group 3), the range of motion decreased by the same amount on both the affected and unaffected sides. The aforementioned observation is convergent with the results of long-term studies concerning the effects of using ankle-foot orthoses in children with cerebral palsy [30].

It should be noted that the limitation of ankle mobility we noted in children with hemiplegic CP should not be equated with actual angular changes in this joint. The trend of change is likely the same in both cases, but the values may differ. In hemiplegic CP, a solid AFO serves two main purposes: limiting movement in the sagittal plane and promoting correction of the foot position (usually remaining in clubfoot position). The quality of these tasks is closely linked to the properties of the worn footwear, which is an integral part of the orthopaedic equipment described here.

Such limitations may constitute the basis for beneficial changes in proximal levels of the biokinematic chain created by the lower limb. This observation is consistent with data [26,31] which have allowed to demonstrate that ankle-foot orthoses indirectly influence the positioning and control of the knee and hip joints. It should be noted that this effect extends higher - to the pelvic girdle, and can be seen not only in the sagittal plane, but also in all major body planes. Such a situation was demonstrated in our previous work [49] on the relationship between solid AFOs and postural stability and symmetry. In this study, only angular changes in the joints of the sagittal plane were reported. This approach was intended to enable the assessment of patients' functional status in line with current trends [53]. In this type of assessment, the primary focus is on angular values recorded in the lower limb joints in the sagittal plane. The values we presented can aid in conducting research in similar groups. It is worth mentioning that the BTS SMART D-140 6 TVC system enables three-dimensional movement analysis [34], one of the elements of which is the characterisation of angular changes in each plane - and the corresponding data are held by the authors of this study. The present observations suggest that ankle-foot orthoses may exert a comprehensive influence on angular changes in the lower limbs and pelvis during gait in children with hemiplegic CP. In addition to the aforementioned findings, the measurement data and results indicate that after putting on ankle-foot orthoses (Groups 2 and 3), the range of pelvic movement improved during gait.

Based on the analysis of the results, we formulated the thesis that increased range of motion during gait in children with hemiplegic CP should be connected with the beneficial effects of AFO use. This is especially true in conditions of bilateral support, which - as presented - favours a reduction in value differences recorded for each side of the body. In the described situation, greater functional shortening of the limb (in the swing phase) occurs than would so if the values for range of motion were low. Therefore, the examined children were able to walk at higher speeds, indicating improved locomotor performance.

The use of solid AFOs may limit functions not directly related to natural gait (stair climbing, sit-to-stand transfers), including through increased physical exertion. Such dilemmas are highly relevant in the context of clinical decision-making. Therefore, it appears that the impact of ankle-foot orthoses is much greater than would be implied solely by their mechanical design. This issue could be elaborated by incorporating neurological functions into advanced kinematic analysis, as was done in [45], using extensive measurement lines for comprehensive studies [13]. This research direction seems to be very promising because optoelectronic measurement systems are becoming increasingly available [34], and technological progress is increasingly directing analyses towards virtual reality [17].

Research limitations

The scope of this study was solely focused on kinematic gait analysis; however, in order to achieve a more complete understanding of gait among children with hemiplegia, further investigations should incorporate dynamic indicators (e.g. torque and muscle power). Although a total of 43 children were evaluated, the size of the individual groups could have limited the quality of the biomechanical analyses. Combined with the large number of statistical tests, it is possible to that the number of positive results may have been overestimated. Moreover, the findings of this study should be interpretated with caution due to the placement of the passive markers directly on the ankle-foot orthoses. This methodology may not be an accurate reflection of the actual value of the angle in this joint, which could be a point of potential scientific debate. The placement of the mentioned markers is based on the researcher's experience and not the devised scientific protocols. Additionally, the type of AFOs (solid) and the necessity of individually adjusting it to the used footwear could have had certain influence on the results. In the analysis of the results of angular changes in the joints of the lower limb and pelvis, focus was solely placed on the sagittal plane, and it has already been proven that AFOs can influence the values recorded in the frontal and transverse planes. The obtained results may be representative mainly for children with a spastic type of hemiplegic cerebral palsy.

The subject of the study was aimed at determining the influence of uni- and bilateral AFOs on the level of gait symmetrisation in children with hemiplegic CP. Nonetheless, focus was placed only on absolute values of the indicators, without using typical measures characterising movement symmetry.

CONCLUSIONS

Analysis of the results obtained in this study indicated that the application of ankle-foot orthoses can have a positive effect on lower limb symmetry during gait performed by children with hemiplegic cerebral palsy, and the noted changes were even more beneficial in patients with bilaterally applied orthoses. This results from the fact that ankle-foot orthoses used by children with hemiplegic cerebral palsy during gait affect not only the joint directly supported by them, but also the other joints of the lower limbs and the pelvis. For that reason, the use of ankle-foot orthoses in children with hemiplegic cerebral palsy may have a positive effect on the angular changes in these segments of the body during gait, which can be conducive to symmetrisation of movement with regard to the affected and unaffected sides of the body.

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