

Article

Kinematic Similarity of Frontal and Transverse Plane Joint Profiles Before and After PRODRobot Gait Training in Children with Neurological Disorders in Relation to Healthy Individuals

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Abstract

Background: Robot-assisted gait training is increasingly used in pediatric neurorehabilitation, but its effects on the full time-course of gait kinematics remain insufficiently understood. This study aimed to determine whether intensive gait training with the automated PRODRobot device could improve frontal- and transverse-plane kinematic profiles in children with neurological disorders and shift them toward the gait pattern of healthy peers. **Methods:** A prospective single-arm pre–post study was conducted in 10 children with cerebral palsy aged 8–13 years who underwent 20 PRODRobot training sessions over 4 weeks. A control group comprised 18 healthy age-matched children. Three-dimensional gait analysis was performed before intervention (KF1) and after intervention (KF2). The primary outcome was the similarity of full frontal- and transverse-plane kinematic waveforms of the hip, knee, and ankle/foot relative to pre–post changes and to the healthy reference profiles, assessed using the difference factor (f_1) and similarity factor (f_2). **Results:** Only two within-group pre–post comparisons met both similarity criteria: hip rotation KF2 versus KF1 ($f_1 = 13.9\%$, $f_2 = 83.7$) and ankle rotation KF2 versus KF1 ($f_1 = 4.1\%$, $f_2 = 67.4$). These findings indicate similarity between the pre- and post-intervention profiles within the intervention group, rather than normalization relative to the control group. In comparisons with healthy controls, most variables retained elevated f_1 values, indicating persistent quantitative deviation from the reference gait pattern. **Conclusions:** PRODRobot-assisted gait training was associated with partial reorganization of selected kinematic waveforms rather than full normalization of gait. The intervention appeared more effective in improving waveform consistency and selected transverse-plane features than in correcting persistent distal and rotational deviations linked to more complex structural or neuromuscular factors.

Keywords: robot-assisted gait training; gait analysis; kinematics; cerebral palsy; pediatric neurorehabilitation



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1. Introduction

Contemporary pediatric rehabilitation is facing a transformation driven by the dynamic development of technology and the growing demand for evidence-based therapies. Cerebral palsy, defined as a group of permanent but non-progressive movement and posture disorders resulting from damage to the developing brain of a fetus or infant, remains the most common cause of motor disability in the pediatric population, with an estimated prevalence of 2.11 cases per 1000 live births [1]. The complexity of the clinical presentation of this condition, encompassing a spectrum ranging from spasticity and dystonia to reduced muscle strength and deficits in selective motor control, poses multidimensional therapeutic challenges, particularly in the area of gait re-education.

Children with CP exhibit characteristic deviations from a normal gait pattern, walk with shorter steps and increased trunk sway, and frequently present with crouch-type flexion gait [2–4]. Their locomotion is less economically efficient in terms of energy expenditure, which manifests as an elevated metabolic cost of walking and reduced biomechanical movement efficiency [3]. Without appropriate therapeutic interventions, the abnormal gait pattern also tends to worsen as the child ages [2,5]. Gait disorders significantly limit the independence and daily activity of pediatric patients, thereby reducing their quality of life [6]. Traditional therapeutic approaches aimed at improving gait include, among others, rehabilitation using classical methods and frequently used treadmill training with body-weight support. Treadmill training has been used for many years in children with CP; however, its effectiveness can be limited, with some reviews indicating no significant improvement in gait function following such intervention [7]. In recent decades, automated robotic devices have therefore been introduced to reduce the physical burden on therapists and increase the intensity of gait training. The introduction of advanced robotics into pediatric rehabilitation was a response to the limitations of conventional therapy, which is physically demanding for therapists, difficult to standardize, and often insufficient in terms of stimulus intensity. As indicated in the literature, robot-assisted training is capable of improving selected gait parameters [8–11]. Nevertheless, publications also exist that report no significant advantage of this type of training over conventional approaches, such as treadmill therapy [12].

The dynamic development of technology has resulted in the emergence of new gait re-education devices dedicated specifically to pediatric patients. One such example is PRO-DROBOT, an automated gait trainer developed in Poland and designed for gait learning and the correction of pathological gait patterns in children with limited motor function [13]. This device is a lower-limb exoskeleton that enables controlled, repeatable movements in the hip, knee, and ankle joints in accordance with correct gait biomechanics [13]. Modern trainers such as PRO-DROBOT allow for intensive locomotion training under conditions that maintain a high level of control and safety.

Verification of the effectiveness of such advanced technologies requires equally advanced analytical tools. Three-dimensional gait analysis is regarded as the gold standard in functional diagnostics, providing comprehensive data on kinematics, kinetics, and spatiotemporal parameters [14–16]. However, in clinical and research practice, this analysis most commonly reduces to the extraction of individual measurement points, which leads to a loss of information regarding the temporal structure of the movement pattern. In the context of evaluating therapy using a robotic gait trainer, it is essential not only to determine whether the maximum value of a given angle has changed, but whether the entire course of movement has undergone normalization [16]. This requires the application of methods for analyzing complete time series [15]. Of key importance is an analysis identifying those regions of the gait cycle in individual lower limb joints that deviate most from reference profiles, which is of significant relevance from the perspective of planning

and evaluating therapy outcomes. The study employed a high-resolution analysis referring to each percentage interval of the relative gait cycle.

The aim of this study was to determine the effectiveness of robot-assisted gait training in children with neurological disorders. The study analyzed changes in gait parameters occurring after a series of training sessions using an automated trainer (PRODROBOT) and assessed the degree to which the kinematic and dynamic gait profiles of the patients approached the reference pattern of healthy peers. Because the available cohort was small, this study was designed as a descriptive, single-arm pre–post analysis. Rather than testing a hypothesis, it aimed to characterize, across the whole gait cycle, which frontal and transverse plane joint profiles changed after robotic device training and to what extent the post-intervention profiles approached the profiles of healthy peers.

2. Materials and Methods

The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee at The Regional Medical Council in Krakow (Nr 76/KBL/OIL/2024).

2.1. Study Design

Initially, 40 individuals participated in the study, in which one independent researcher performed the selection based on guidelines provided on a sheet of paper by the main research team, without being informed about the course of the study. The guidelines contained information regarding the participant screening procedure in order to select the most somatically similar research sample. The preliminary assumptions included criteria such as: a signed consent form from the legal guardian for participating in the study, completed medical qualification for therapy and research, aged between 8 and 13 years, and body weight including clothing not exceeding 50 kg. On this basis, 30 participants were selected and subsequently subjected to further assessment according to established inclusion and exclusion criteria. Of the 12 children who qualified for the intervention group, two did not complete the protocol for reasons unrelated to the intervention: one withdrew because of COVID-19 organizational restrictions that prevented attendance, and one died during the study period from causes related to the pre-existing underlying condition and unrelated to the PRODROBOT training or to any study procedure. The final analyzed intervention group therefore comprised 10 children. The control group consisted of 18 healthy children with parameters similar to those of the intervention group.

No adverse events attributable to the device or the intervention itself were recorded in any participant. Sessions were supervised a trained team, and participants were continuously monitored for loss of pattern quality or signs of exercise intolerance. No adverse events occurred during the study.

Detailed inclusion and exclusion criteria are presented in Table 1.

The study was designed as a single-arm prospective pre- and post-intervention study with two measurement points: KF1 before the commencement of therapy and KF2 after completion of the cycle. The study lasted a total of 2 months, including a 5-week intervention process along preliminary and main assessments and measurements.

Table 1. Eligibility criteria for participation in the study.

Inclusion Criteria	Exclusion Criteria
The ability to independently cover a distance of 30 m multiple times	Significant muscle contractures preventing the reproduction of locomotor movements in the lower limb joints within the regulatory range of the gait trainer
Limited length of lower limb segments, determining the distance between the joints: ankle and knee, knee and hip. The lengths of the thigh and shank segments should fall within the range of 29 cm to 37 cm.	Arthrodesis of the hip, knee, and ankle joints
Total body height of the patient within the range of 1.1 m to 1.5 m	Active implants
The maximum width of the pelvis measured on the outer side of the upper edge of the iliac crest must not exceed 0.3 m	Bone instability (unstabilized fractures, unstable spine, advanced osteoporosis)
Present neurological dysfunction	Extremely disproportionate limb and/or spinal length (e.g., osteochondral dysplasias); serious vascular disorders within the lower limbs

2.2. Participants

The intervention group consisted of 10 individuals aged between 8 and 13 years. All intervention participants had a confirmed diagnosis of spastic cerebral palsy at level 3 on the GMFCS; no other neurological etiologies were represented, so the sample was diagnostically homogeneous. The mean age of the participants was 9.6 ± 2.45 years, and body height, determined from markers describing the position of the body segments, was 1.31 ± 0.13 m. Body mass was 31.25 ± 9.47 kg. Within the group, the highest participant body mass was 48.5 kg, while the lowest was 19 kg. The parameter defining the maximum pelvic width in the study group averaged 0.236 ± 0.03 m. The body mass index (BMI) was also calculated for the participants, averaging 17.63 ± 1.998 kg/m² across the group. The detailed inclusion criteria have been previously described in Table 1. Informed consent for participation in the study was obtained from the legal guardians of all participants, as well as consent from the attending physician.

The control group consisted of 18 healthy individuals aged between 7 and 14 years. The mean age was 10.1 ± 2.42 years, body height was 1.34 ± 0.12 m, and body mass was 32.36 ± 7.27 kg. Within the group, the highest participant body mass was 50.2 kg, while the lowest was 22.4 kg. The parameter defining the maximum pelvic width averaged 0.241 ± 0.028 m. The mean BMI value in the control group was 17.85 ± 2.10 kg/m².

The intervention and control groups were statistically comparable in anthropometry (Table 2). Two-tailed Welch *t*-tests showed no significant between-group differences in age, body height, body mass, pelvic width, or BMI ($p > 0.55$; $d < 0.25$).

For each of the studied groups, spatiotemporal gait parameters were calculated and are presented in Table 3.

Table 2. Between-group comparison of anthropometric characteristics.

Parameter	Intervention	Control	t	df	p	d
Age [years]	9.60 ± 2.45	10.10 ± 2.42	−0.52	18.5	0.609	−0.21
Body height [m]	1.31 ± 0.13	1.34 ± 0.12	−0.60	17.5	0.555	−0.24
Body mass [kg]	31.25 ± 9.47	32.36 ± 7.27	−0.32	15.0	0.752	−0.14
Pelvic width [m]	0.236 ± 0.030	0.241 ± 0.028	−0.43	17.6	0.671	−0.17
BMI [kg/m ²]	17.63 ± 2.00	17.85 ± 2.10	−0.27	19.5	0.787	−0.11

BMI—body mass index; *t*—Welch’s *t*-test; *df*—degrees of freedom; *p*—probability value; *d*—Cohen’s effect size.

Table 3. Values of spatiotemporal gait parameters in the studied groups of individuals.

STP (Spatiotemporal Parameters)	KF1		KF2		CG	
	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
WS (walking speed) [ms ^{−1}]	0.91	0.07	0.93	0.07	1.01	0.08
STRT (stride time) [s]	1.04	0.06	1.02	0.07	1.07	0.05
STRL (stride length) [m]	0.95	0.08	0.91	0.07	0.94	0.09
CAD (cadence) [Hz]	1.92	0.12	1.96	0.13	1.85	0.08
DSAP (double support time) [%]	21	2.4	22	2.5	25	2.2
SSAP (single support time) [%]	39	2.1	38	4.2	37	3.3
OFO (foot off) [%]	61	1.7	61	1.1	62	1.2

STP—spatiotemporal parameters; WS—walking speed; STRT—stride time; STRL—stride length; CAD—cadence; DSAP—double-support time; SSAP—single-support time; OFO—foot-off expressed as a percentage of the gait cycle; KF1—pre-intervention measurement; KF2—post-intervention measurement; CG—control group; $\bar{x}$ —mean; s—standard deviation.

2.3. Data Collection and Testing Procedure

Each participant underwent an identical preparatory procedure. The measurement procedure involved the recording of kinematics during free walking under laboratory conditions. Movements of the trunk, pelvis, neck, and hips were recorded in three planes using the Vicon 3D system, and longitudinal and lateral stability indices were calculated. For each participant, 15 gait cycles (30 steps) of a fixed length were collected. The Vicon Nexus software (version 2.19) automatically calculated the standard spatiotemporal gait parameters, including walking speed, stride length, stride time, cadence, single-support time, double-support time, and foot-off timing. These parameters were used to characterize the gait performance of the intervention and control groups and to confirm their overall spatiotemporal comparability before the waveform-based kinematic analysis. The time signals were normalized as a relative percentage of the gait cycle, and the results were then averaged within each individual’s gait stereotype. For each participant, the 15 recorded gait cycles were first averaged point by point to obtain one representative kinematic profile. Subsequently, these individual profiles were averaged point by point across participants to obtain the mean group profile for each analyzed joint in the intervention and control groups. The primary endpoints were defined as the change from KF1 to KF2 in measures of fit to the reference pattern of angular changes of axial segments in the joints and in the range of longitudinal stability. The fit measures included the mean absolute error relative to the reference curve averaged over the cycle, the root mean square error averaged over the cycle, and the Pearson correlation coefficient calculated between the individual’s profile and the reference profile. Quality of life was assessed with the Cerebral Palsy Quality of Life (CP-QOL) questionnaire before and after the intervention. Scores changed from 65.4 ± 12.3 to 70.1 ± 11.8 ($n = 10$). For the purposes of clinical interpretation, percentage changes relative to the baseline values were calculated, as well as the number of individuals exceeding the clinical significance thresholds where applicable.

2.4. Equipment and Intervention

The intervention consisted of gait re-education using the fully automated PRO-DROBOT gait trainer by PRODRAMUS (Kraków, Poland) with axial segment control. Support parameters were selected individually based on functional assessment and subsequently modified progressively in order to achieve 10,000 step cycles while maintaining safety and pattern quality over the course of 20 training sessions conducted over a period of 4 weeks (5 sessions per week), with each session comprising approximately 500 step cycles, corresponding to approximately 8–10 min of effective walking. During the sessions, walking speed, stance and swing phase times, ranges of motion in the axial segments, and subjective effort were monitored, while progression criteria included the maintenance of pattern quality and the absence of symptoms of exercise intolerance. The entire intervention cycle was standardized and conducted by a trained team.

2.5. Statistical Analysis

The analysis covered angular changes in the lower limb joints, including the ankle, knee, and hip joints. The kinematic data were processed to obtain complete time series for the movement cycle in three anatomical planes. Because gait kinematics are continuous curves, we compared complete time-normalized waveforms rather than isolated points, which would discard information about the temporal structure of movement. Similarity between any two profiles was quantified with two model-independent indices adapted from the comparison of dissolution profiles: the difference factor f_1 and the similarity factor f_2 (Equations (1) and (2)). These indices require no parametric functional model of the curve and no point-wise multiple-comparison correction, which makes them appropriate for a small, clinically heterogeneous sample in which the distributional and cluster-inference assumptions of statistical parametric mapping (SPM) are difficult to satisfy and would be characterized by low statistical power. To express variability, each reference profile is reported as a mean $\pm$ 1 SD corridor, and the between-participant SD of the intervention group is reported at each 1% of the cycle. We deliberately did not apply null-hypothesis significance tests to the waveforms; the analysis is descriptive and quantifies the magnitude and cycle-timing of profile differences. No a priori sample-size calculation was performed; therefore, given the final intervention sample of $n = 10$, the waveform analysis was treated as exploratory and descriptive rather than confirmatory. We regard SPM and its non-parametric permutation variant as complementary whole-waveform methods; their formal application in an adequately powered, diagnostically stratified cohort is a priority for future work.

No a priori sample-size calculation was performed; the sample was one of convenience, constrained by the eligibility window and the anthropometric limits of the PRODRobot device. With a final intervention group of $n = 10$, the study was statistically underpowered for confirmatory testing, and no formal null-hypothesis tests were applied to the kinematic waveforms. The analysis is consequently descriptive: it quantifies the magnitude and cycle-timing of profile differences rather than establishing their statistical significance. Results should be regarded as preliminary and requiring confirmation in an adequately powered, diagnostically stratified sample.

In order to verify the consistency and repeatability of movement patterns, a detailed analysis of the similarity of kinematic profiles was conducted. This assessment allowed for the determination of the degree of similarity between the recorded profiles and the reference pattern of the control group. Two factors were applied in the calculations: the difference factor f_1 and the similarity factor f_2 , defined in Equations (1) and (2) [17,18]. Both factors were model-independent, meaning they did not require the description of variable profiles using a mathematical function.

The difference factor f_1 , expressing the averaged percentage error between the reference curve and the second examined curve throughout the entire gait cycle, was adopted as the measure of discrepancy between the analyzed profiles. This value was calculated according to the equation:

$$f_1 = \frac{\sum_{t=1}^n |T_1 - T_2|}{|\sum_{t=1}^n T_1|} 100 [\%], \quad (1)$$

Equation (1). Profile difference factor [17,18].

The analysis was complemented by the determination of the similarity factor f_2 , which is a logarithmic transformation of the sum of squared errors. This index is a measure sensitive to deviations in instantaneous values and is defined by the formula:

$$f_2 = 50 \log \left\{ 1 + \left[\frac{\sum_{t=1}^n (T_1 - T_2)^2}{n} \right]^{\frac{1}{2}} \right\} 100 [\%] \quad (2)$$

Equation (2). Similarity factor value [17,18].

Where T_1 and T_2 represent the instantaneous joint-angle values, expressed in degrees, for the two compared kinematic profiles at each normalized point of the gait cycle, and n denotes the total number of measurement points. The gait cycle was normalized from 0% to 100% at 1% intervals, resulting in $n = 101$ points. Each waveform was time-normalized by linear interpolation to 101 equally spaced points representing 0–100% of the gait cycle. Two kinematic profiles were considered biomechanically similar when two conditions were simultaneously met: the value of the difference factor $f_1 < 15\%$ and the value of the similarity factor f_2 fell within the range $50 < F_2 \leq 100$.

3. Results

Table 4 presents the difference factor (f_1) and similarity factor (f_2) values for the compared frontal- and transverse-plane kinematic profiles of the foot, knee, and hip. Both similarity criteria were simultaneously met only for the within-group pre–post comparisons of foot progression angle (KF2 vs. KF1; $f_1 = 4.1$, $f_2 = 67.4$) and hip rotation (KF2 vs. KF1; $f_1 = 13.9$, $f_2 = 83.7$). These pairs were therefore classified as similar. None of the comparisons between the post-intervention profiles and the control group met both similarity criteria. Several remaining pairs showed high f_2 values, indicating similarity in waveform shape, but failed to meet the f_1 threshold for acceptable quantitative difference.

Figure 1a presents the mean abduction/adduction angle profiles at the hip joint in the normalized gait cycle for the experimental group before intervention (KF1), after intervention (KF2), and the control group (CG). The range of motion in the frontal plane at the hip joint for KF1 ranged from approximately -5.0° (adduction) to 9.8° (abduction), while for the reference pattern, it ranged from -5.7° to 8.8° . The range of angular changes in CG was slightly smaller throughout the cycle by $1\text{--}1.5^\circ$. The intervention may have caused a slight shift in the range of hip joint adduction toward the neutral position during part of the stance phase from 0–40% of the cycle, as well as an increase in hip abduction of approximately 2° during the swing phase from 70–100% of the cycle. This resulted, on the one hand, in a more symmetrical distribution of the abduction/adduction ranges of motion at the joint throughout the cycle, but simultaneously caused the range of motion of KF2 to diverge from the results of the control group.

Table 4. Difference factor (f1) and similarity factor (f2) for comparisons of frontal- and transverse-plane kinematic profiles between the pre-intervention (KF1), post-intervention (KF2), and control group (CG) measurements.

Variable Pairs—Frontal and Transverse Plane	f1	f2
FOOT PROGRESSION ANGLE_KF2 vs. FOOT PROGRESSION ANGLE_KF1	4.1	67.4
FOOT PROGRESSION ANGLE_KF1 vs. FOOT PROGRESSION ANGLE_CG	12.3	45.0
FOOT PROGRESSION ANGLE_KF2 vs. FOOT PROGRESSION ANGLE_CG	16.4	45.0
FOOT INVERSION/EVERSION_KF2 vs. FOOT INVERSION/EVERSION_KF1	75.1	96.8
FOOT INVERSION/EVERSION_KF1 vs. FOOT INVERSION/EVERSION_CG	76.8	84.0
FOOT INVERSION/EVERSION_KF2 vs. FOOT INVERSION/EVERSION_CG	97.1	84.0
KNEE VALGUS/VARUS_KF2 vs. KNEE VALGUS/VARUS_KF1	63.2	94.0
KNEE VALGUS/VARUS_KF1 vs. KNEE VALGUS/VARUS_CG	95.3	93.3
KNEE VALGUS/VARUS_KF2 vs. KNEE VALGUS/VARUS_CG	73.8	93.5
KNEE ROTATION_KF2 vs. KNEE ROTATION_KF1	50.7	96.7
KNEE ROTATION_KF1 vs. KNEE ROTATION_CG	87.1	97.6
KNEE ROTATION_KF2 vs. KNEE ROTATION_CG	55.1	97.5
HIP ABDUCTION/ADDUCTION_KF2 vs. HIP ABDUCTION/ADDUCTION_KF1	24.6	89.6
HIP ABDUCTION/ADDUCTION_KF1 vs. HIP ABDUCTION/ADDUCTION_CG	33.5	86.0
HIP ABDUCTION/ADDUCTION_KF2 vs. HIP ABDUCTION/ADDUCTION_CG	42.0	86.0
HIP ROTATION_KF2 vs. HIP ROTATION_KF1	13.9	83.7
HIP ROTATION_KF1 vs. HIP ROTATION_CG	72.4	69.0
HIP ROTATION_KF2 vs. HIP ROTATION_CG	51.9	69.0

KF1—pre-intervention measurement; KF2—post-intervention measurement; CG—control group. Kinematic profiles were considered similar when both criteria were met: $f1 < 15\%$ and $50 < f2 \leq 100$.

The analysis of the absolute difference modules of the analyzed curves indicates the occurrence of the greatest differences between the curves at the beginning of the stance phase at approximately 5% of the cycle and during the swing phase from approximately 70 to 100% of the cycle. The difference modules did not exceed a value of 2%. The abduction/adduction angle change curve in the control group differed most from the KF1 curve at approximately 5, 40, and 90% of the gait cycle, i.e., during the initial foot loading phase, the mid-stance phase, and the final swing phase, where it reached its highest value of approximately 3%.

A distinct improvement in the KF2 curve relative to KF1 and CG was observed during the LR phase at approximately 7 and 22% of the cycle, as well as at the transition from the contact phase to the swing phase, where the curve did not differ from the angular change profile of the control group CG. The greatest similarity of the KF1 curve to CG was also noted in the area of the transition from the contact phase to the swing phase. The highest absolute values of the difference module (approximately 4.5%) were recorded between the KF2 and CG curves at approximately 90% of the cycle, as already indicated above in the description of the symmetrization of angle changes (Figure 1a).

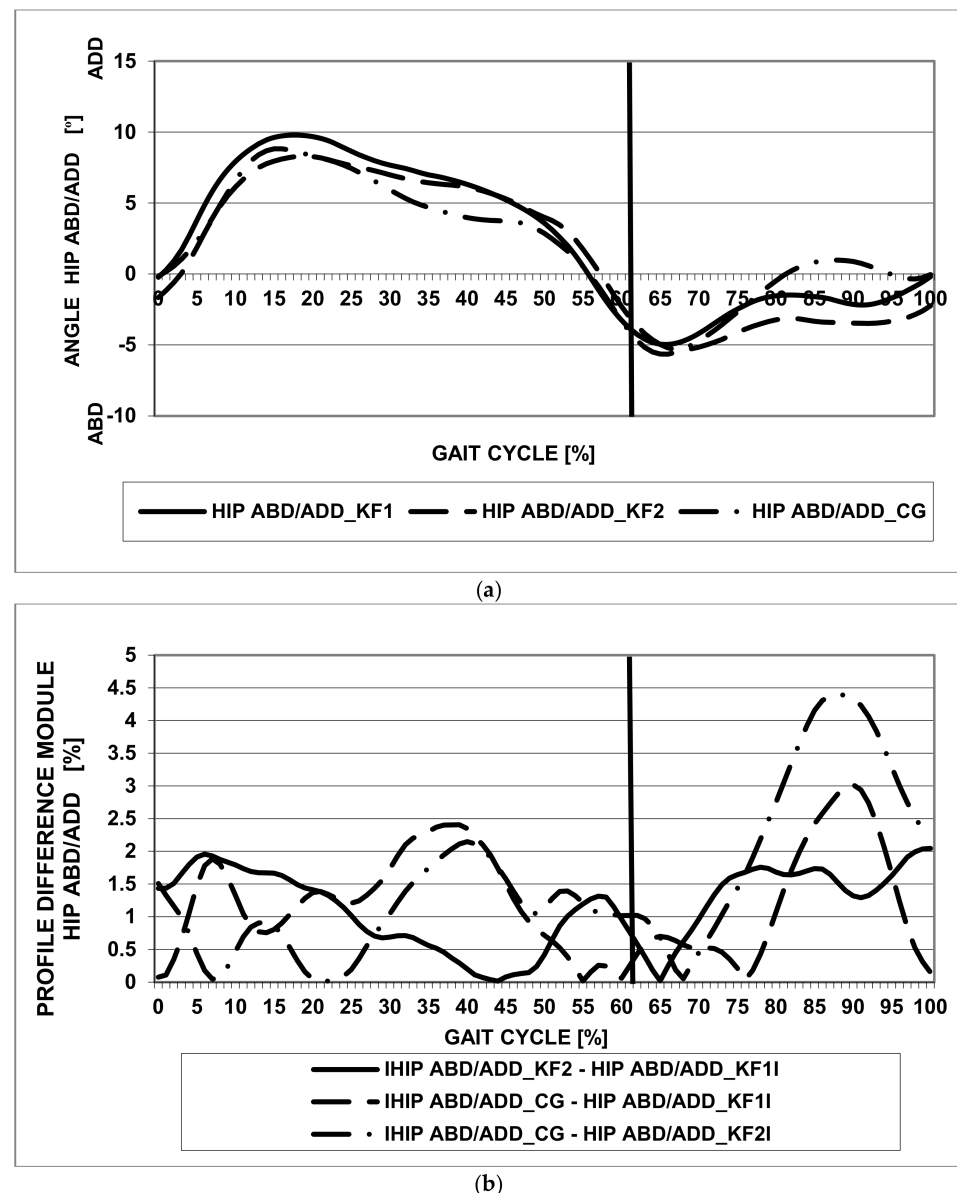


Figure 1. (a) Abduction/adduction curves of the hip joint in the normalized gait cycle; (b) difference profiles between the abduction/adduction curves of the hip joint. This vertical line is the moment the toes leave the ground—toe-off (TO), which is the boundary between the two main phases of the gait cycle.

Figure 2a illustrates the profile of the internal and external rotation angle at the hip joint. Comparison of the KF2 vs. KF1 pair demonstrated the simultaneous fulfillment of both similarity criteria ($f1 = 13.9\%$; $f2 = 83.7\%$), which allowed these profiles to be classified as biomechanically similar. The value of $f1$ not exceeding the 15% threshold suggests, however, that despite the preservation of the rotation pattern shape and amplitude, the quantitative differences between KF1 and KF2 are borderline.

Both the KF1 and KF2 curves are characterized by a shifted range of angular changes in the direction of internal rotation relative to CG throughout the entire gait cycle. The greatest range of motion was recorded in the KF2 group (12°), and correspondingly in the KF1 group (11°) and CG (11°). The curves differed from one another, however, in individual phases of the cycle. The greatest difference occurred during the stance phase, where the hip internal rotation angle in the participants remained higher by approximately 5° compared to the normal pattern represented by CG (Figure 2a). During the initial

swing phase ISW and mid-swing phase MSW, the KF2 curve reduced these differences relative to CG to approximately 2° , indicating an improvement in hip joint movement in the transverse plane.

Comparing the differences between the curve profiles (Figure 2b), it should be noted that the KF1 and KF2 curves differed most from each other between 25–30% (module difference at approximately 2%) and 65–70% of the cycle (module difference at approximately 4%). They were most similar to each other during the LR phase and TSW (terminal swing), where the value of the difference module decreased to approximately 0.5%.

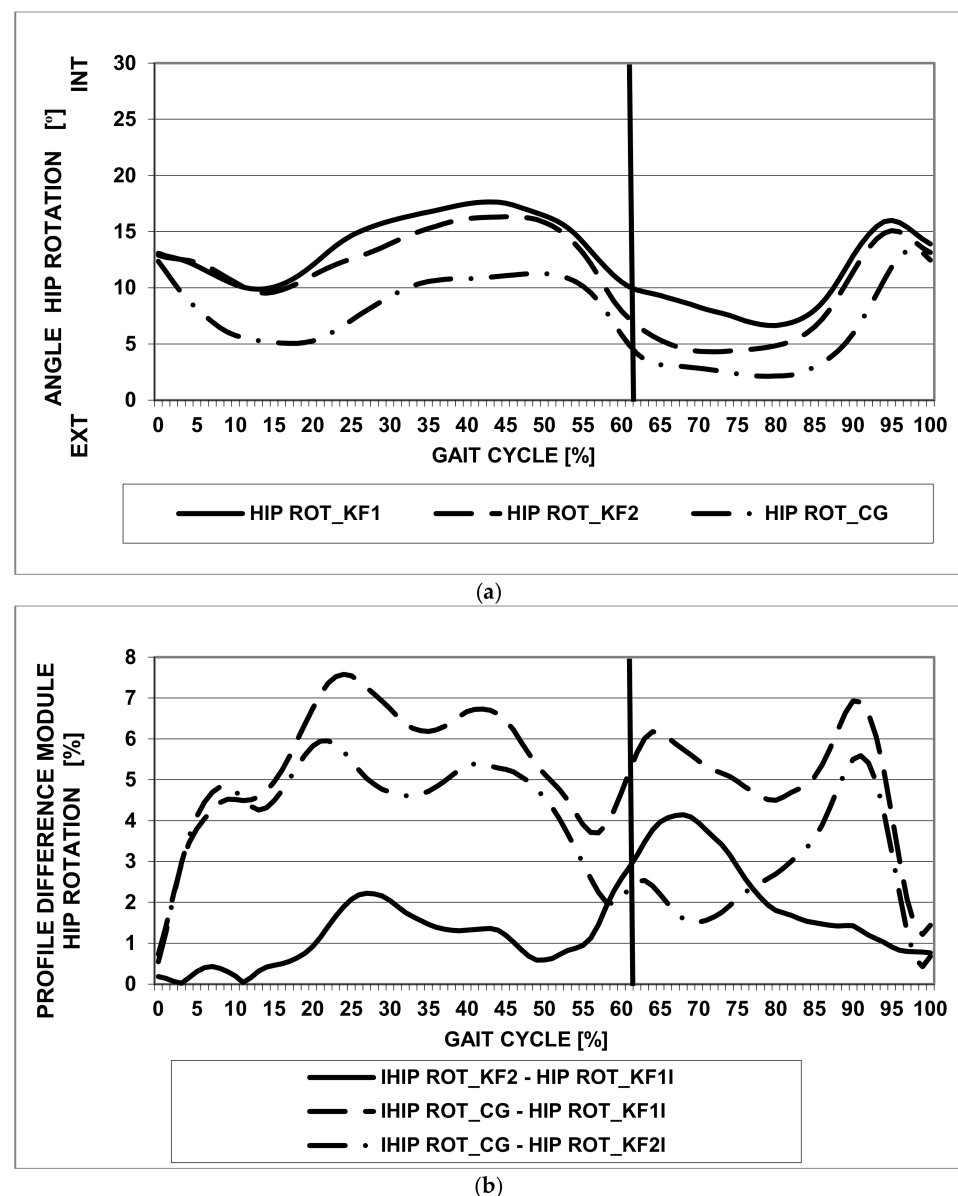


Figure 2. (a) Internal/external rotation curves of the hip joint in the normalized gait cycle; (b) difference profiles between the internal/external rotation curves of the hip joint. This vertical line is the moment the toes leave the ground—toe-off (TO), which is the boundary between the two main phases of the gait cycle.

The KF1 and CG curves differed most from each other at approximately 25, 40, 65, and 90% of the cycle, where the maximum value of the difference module reached a level of 7.5%. The greatest similarity between the curves was in turn noted during the terminal swing phase TSW and at the moment of initial contact IC. The effects of therapy can be observed through a distinct reduction in differences in KF2–CG comparisons. The greatest

changes were observed during the initial swing phase at 65–70% of the cycle, where the values of the difference module decreased from a level of 6 to 1.5% relative to the KF1–CG curve comparisons. It should be emphasized that the positive changes were initiated somewhat earlier during the TST (terminal stance) phase. The greatest similarity of the KF2 curve relative to CG was recorded during the terminal swing phase and the initial foot loading phase from 98–2% of the cycle.

Figure 3a presents the profiles of the varus/valgus angle of the knee joint, which does not represent a degree of freedom in the joint, but rather reflects the alignment of the shank relative to the thigh in the frontal plane throughout the gait cycle. High values of the similarity factor f_2 were obtained for all analyzed pairs (KF2 vs. KF1: 94.0; KF1 vs. CG: 93.3; KF2 vs. CG: 93.5). These values were among the highest of all the analyzed variables.

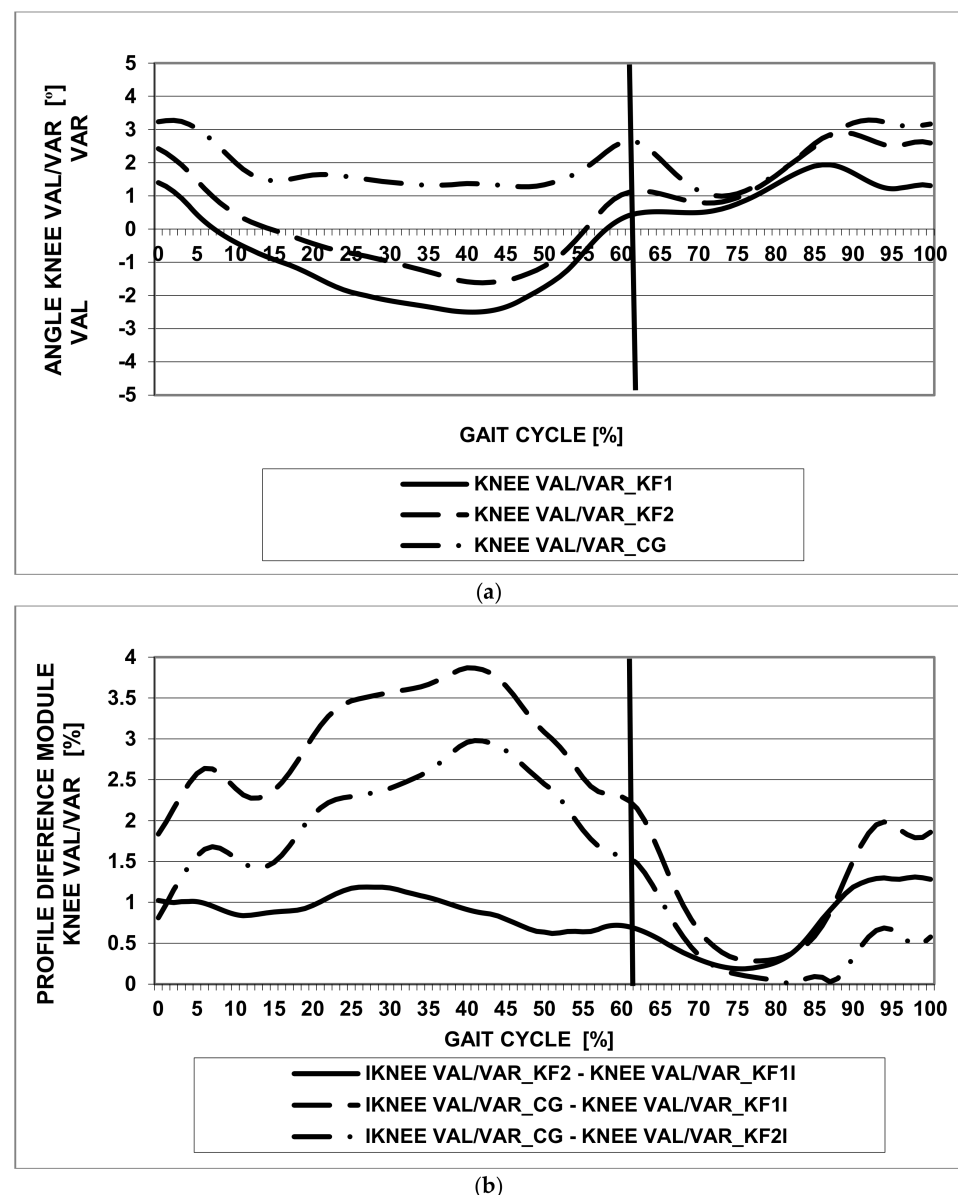


Figure 3. (a) Varus/valgus curves of the knee joint in the normalized gait cycle; (b) difference profiles between the varus/valgus curves of the knee joint. This vertical line is the moment the toes leave the ground—toe-off (TO), which is the boundary between the two main phases of the gait cycle.

Despite the high shape similarity, the values of the difference factor f_1 were elevated in all pairs (KF2 vs. KF1: 63.2%; KF1 vs. CG: 95.3%; KF2 vs. CG: 29.1%), repeatedly exceeding

the 15% threshold. On the difference profile (Figure 3b), a relatively constant difference was visible that persisted throughout most of the gait cycle, with slight intensifications during the loading response phase (0–10% of the cycle) and during the terminal stance phase (30–50% of the cycle). Following the intervention (KF2), a reduction in the f1 value relative to CG was noted (from 95.3% in KF1 to 29.1% in KF2), which may indicate a reduction in quantitative differences.

Figure 4a presents the profiles of internal/external rotation at the knee joint. The similarity factor f2 reached the highest values of all analyzed variables (KF2 vs. KF1: 96.7; KF1 vs. CG: 97.6; KF2 vs. CG: 97.5), indicating an almost identical shape of the knee rotation curves across all compared groups. At the same time, the values of f1 considerably exceeded the threshold of permissible differences (KF2 vs. KF1: 50.7%; KF1 vs. CG: 87.1%; KF2 vs. CG: 29.1%).

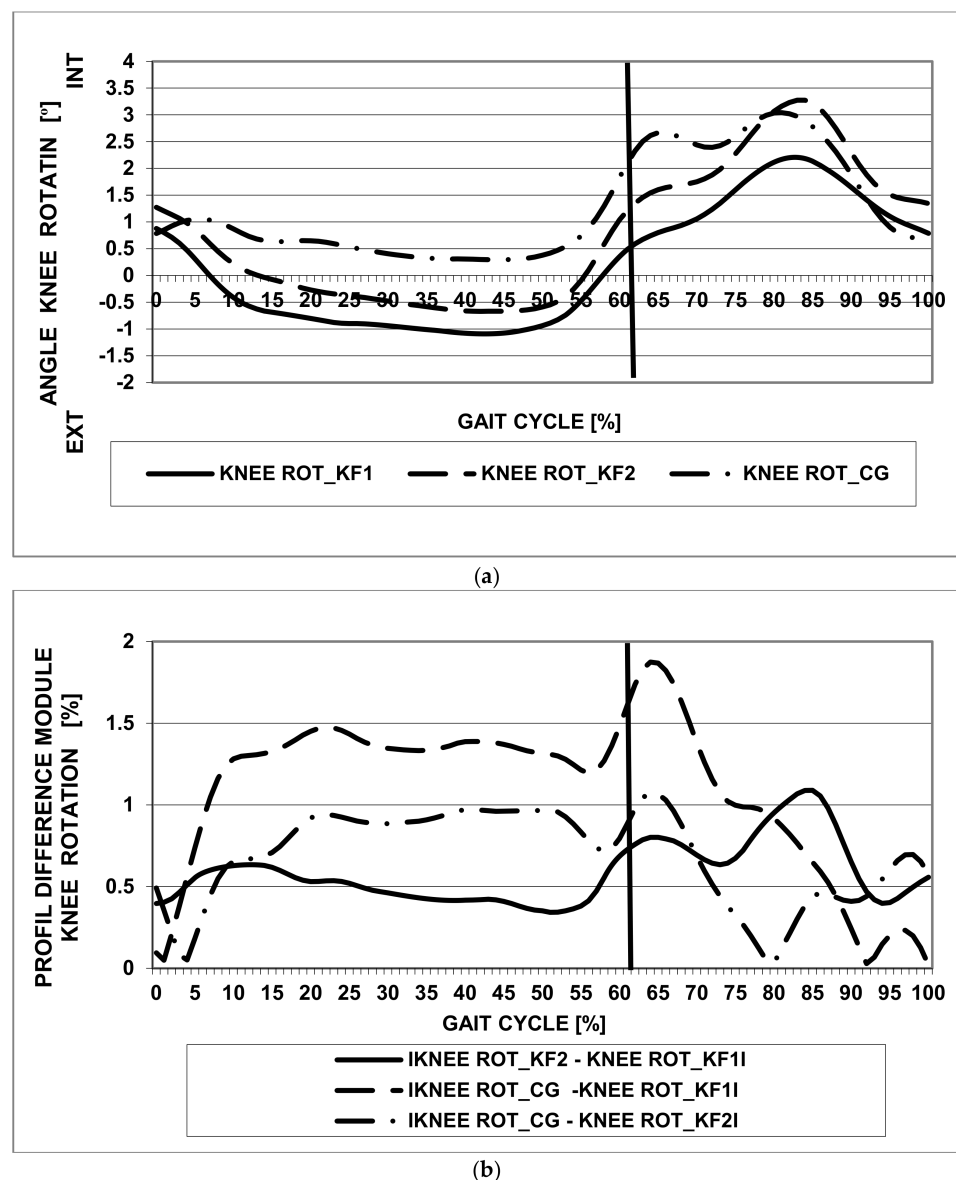


Figure 4. (a) External/internal rotation curves of the knee joint in the normalized gait cycle; (b) difference profiles between the external/internal rotation curves of the knee joint. This vertical line is the moment the toes leave the ground—*toe-off* (TO), which is the boundary between the two main phases of the gait cycle.

The ranges of rotational motion at the knee joint were similar and ranged from 4° to 4.5° . The KF1 and KF2 curves, despite having similar ranges of motion as in CG, were shifted in the direction of internal rotation relative to the control group. Following the intervention, the rotational movement of the knee coincided with the physiological range in the area of external rotation. The mean angular value in the transverse plane of the knee increased for KF2 in the direction of external rotation, approaching the level of CG (1.3°), Figure 4a. In Figure 4b, the analysis of difference modules between the curve profiles revealed the greatest differences between 10 and 50% of the cycle and at 65%, immediately after foot lift-off from the ground. These decreased by approximately 1% in the follow-up assessment relative to KF1. The greatest differences between the KF1 and KF2 curves occurred in the middle part of the swing phase MSW, but were only slightly smaller than in the KF1–CG and KF2–CG comparisons.

Figure 5a illustrates the profiles of the foot inversion/eversion angle throughout the gait cycle. The similarity factor f_2 assumed high values for all pairs (KF2 vs. KF1: 96.8; KF1 vs. CG: 84.0; KF2 vs. CG: 84.0), indicating preserved shape similarity of the profiles. However, the values of f_1 were significantly elevated (KF2 vs. KF1: 75.1%; KF1 vs. CG: 76.8%; KF2 vs. CG: 29.1%), indicating quantitative differences in the ranges of inversion and eversion.

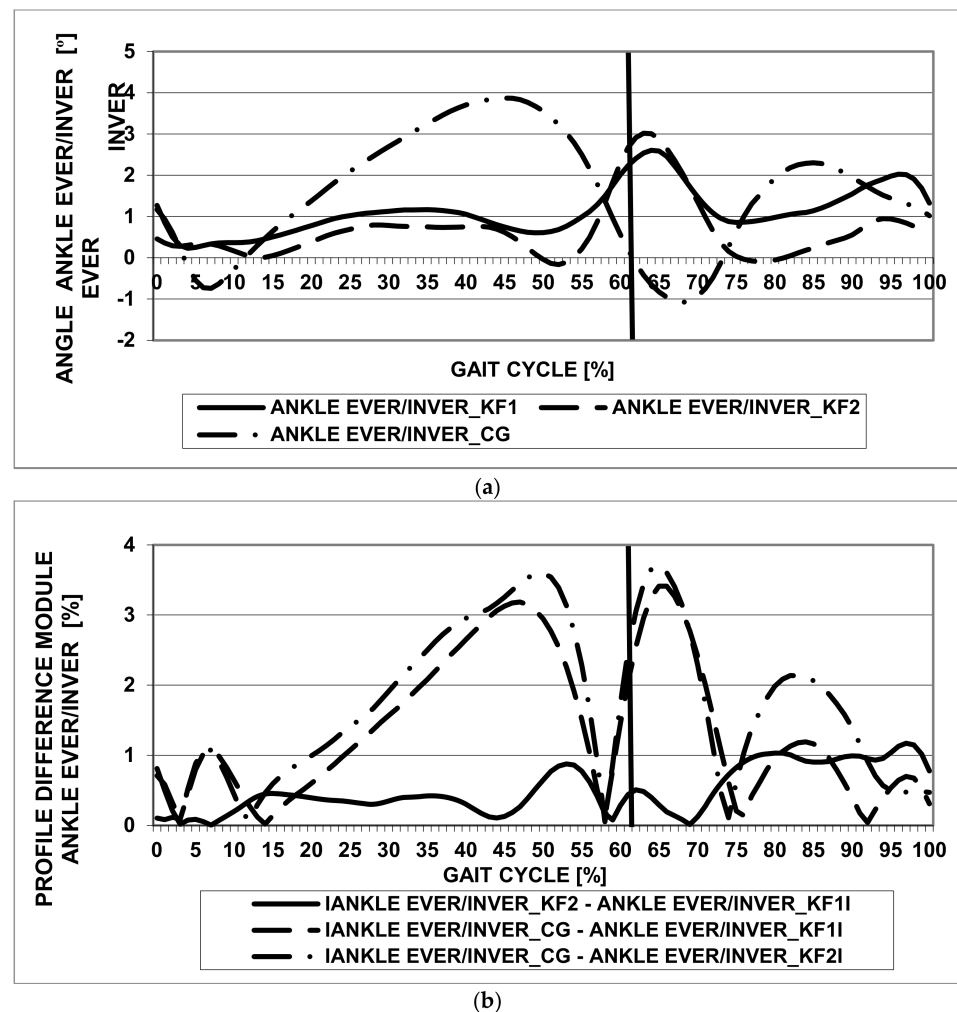


Figure 5. (a) Foot inversion/eversion profiles over the normalised gait cycle (KF1, KF2, CG); (b) absolute difference profiles between the inversion/eversion curves. This vertical line is the moment the toes leave the ground—*toe-off* (TO), which is the boundary between the two main phases of the gait cycle.

In KF1, this movement occurred within a narrower range than the range of changes in CG, and almost exclusively on the inversion side. The minimum recorded value in KF1 was -0.2° , which indicated a virtually complete absence of eversion; the foot did not reach a neutral position, while the maximum inversion reached 2.6° . For comparison, in the reference profile, the foot angle changed from -1.1° to 3.9° . Following the intervention, a slight improvement in mobility in the direction of eversion occurred: in KF2, the minimum angle was -0.2° , indicating the appearance of minimal foot eversion. The maximum inversion increased slightly to 3° . The mean angle in the frontal plane of the foot decreased from 1.1° (KF1) to 0.7° (KF2) of inversion, while the reference mean was 1.6° , (Figure 5a).

In Figure 5b, two larger peaks and one slightly smaller peak were visible, indicating greater differences between the KF1–CG and KF2–CG curves. These occurred at approximately 50 and 65% of the cycle, corresponding to the PSW and ISW phases, respectively. The third smaller peak occurred during the mid-swing phase MSW. It should be noted that greater differences relative to the CG curve were recorded following therapy, which could indicate a slight deterioration of results at the ankle joint in this plane of motion. However, the differences were not significant and did not exceed a value of 1% of the difference module. The differences between the KF1 and KF2 curves oscillated between 0.5 and 1% of the difference module value.

Figure 6a presents the profiles of the foot rotation angle (foot progression angle) throughout the gait cycle. Comparison of the KF2 vs. KF1 pair demonstrated the simultaneous fulfillment of both similarity criteria: $f1 = 4.1\%$ (well below the 15% threshold) and $f2 = 67.4$ (above the 50 threshold). This result indicates that the foot progression angle profiles before and after the intervention were similar to each other both in terms of shape and absolute values. The low value of $f1$ (the lowest among all analyzed variable pairs) indicates small quantitative differences between the KF1 and KF2 measurements for this variable.

The reference pattern was characterized by a constant outward foot position, with angle values being negative throughout the entire cycle. Both the KF1 and KF2 curves had a shifted range of motion in the direction of internal rotation. In the pre-intervention state (KF1), a clear deviation from this norm was observed: the foot rotation angle changed from -14.2° to 10.6° . This means that the participants did not maintain the physiological external rotation of the foot; in some phases, internal foot rotation reaching 10° appeared. Following the intervention, the values increased, with the range spanning from -8.7° to 13.5° . The maximum external rotation decreased to -8.7° compared to -14.2° before the intervention and -23° in the reference, while the value of internal foot rotation increased.

Analyzing the difference modules of the curve profiles, it should be noted that the highest difference values between KF1 and CG were recorded in the first part of the stance phase and the swing phase, reaching values of 23%, which indicates significant differences between the curves in these phases. Values of the difference module approximately 5% lower were recorded in analogous phases in KF1–CG comparisons.

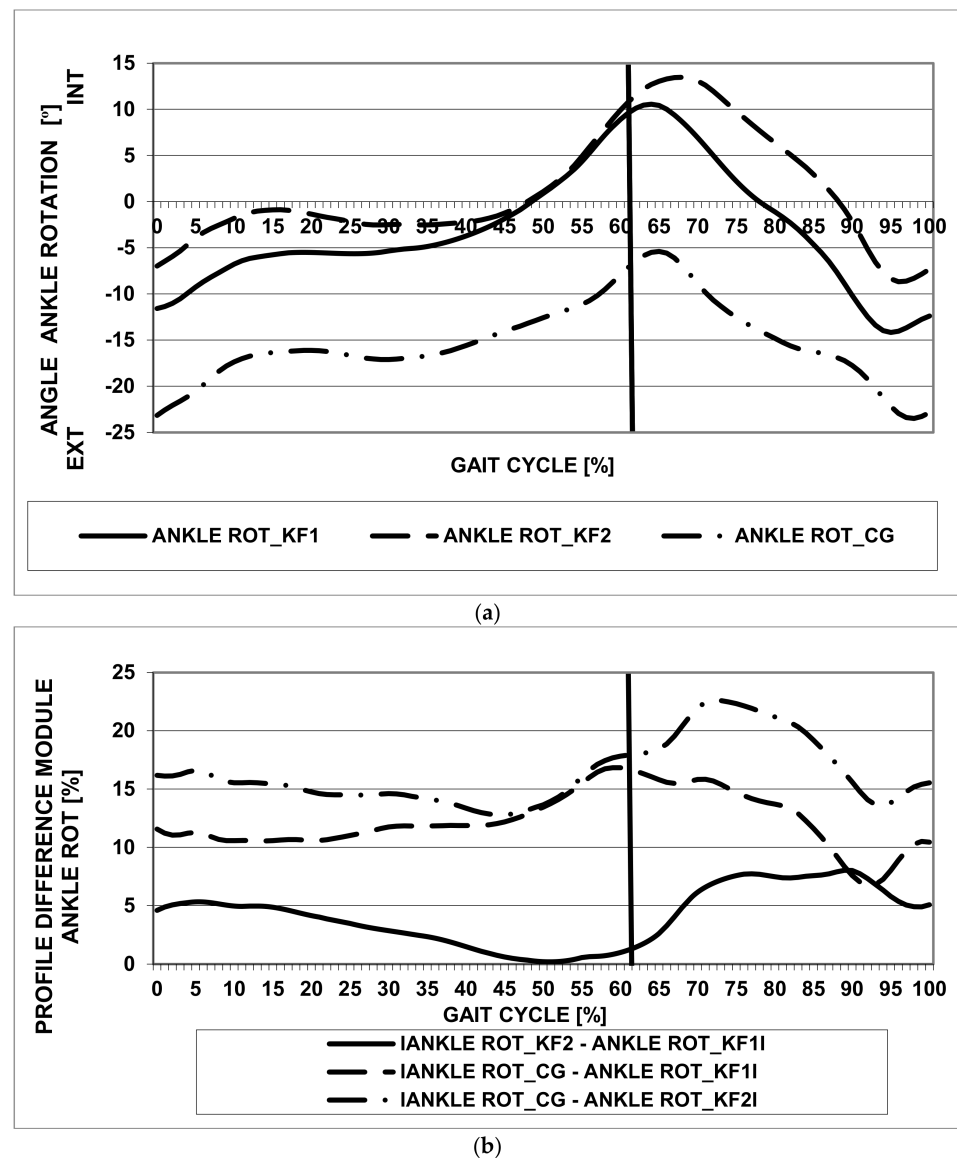


Figure 6. (a) Foot progression angle (transverse-plane foot rotation) over the normalized gait cycle (KF1, KF2, CG); (b) absolute difference profiles between the foot progression-angle curves. This vertical line is the moment the toes leave the ground—*toe-off* (TO), which is the boundary between the two main phases of the gait cycle.

4. Discussion

The aim of the study was to assess whether intensive robot-assisted gait training using the PRODROBOT device leads to an approximation of the kinematic gait profiles of children with neurological disorders to the reference pattern of healthy peers. The obtained results indicate that the response to the intervention was heterogeneous and depended both on the analyzed joint and on the plane of motion. Given the final intervention sample of $n = 10$, these findings should be interpreted as descriptive and exploratory rather than confirmatory. The most important observation is that full normalization of the analyzed profiles was not achieved following therapy; however, in some variables, a reduction in quantitative differences relative to the control group or a reduction in the difference from the reference profile in selected portions of the gait cycle was noted. At the same time, the analysis based on the f1 and f2 indices showed that similarity in the shape of the profiles does not always indicate their actual approximation to the norm, as in many cases, a high level of similarity coexisted with a persisting shift in absolute values.

With regard to the hip joint in the frontal plane, the abduction and adduction profiles were already relatively close to the reference values prior to the intervention. Following therapy, a slight shift of adduction toward a more neutral position was noted during part of the stance phase, along with an increase in abduction during the swing phase. From a biomechanical standpoint, this can be interpreted as the effect of a more symmetrical organization of movement within the pelvis and hip; however, this did not translate into an unambiguous approximation of the entire profile to the control group. This result suggests that in the frontal plane of the hip, the intervention may have organized the temporal course of movement without producing a clear reduction in all quantitative deviations. This is consistent with observations that in robot-assisted training, it is easier to achieve greater pattern repeatability than full normalization of its amplitude, particularly when baseline deviations are not substantial [19–21].

In the transverse plane of the hip, one of the most clearly readable effects of therapy was obtained. The KF2 versus KF1 pair fulfilled both similarity criteria, and the analysis of the profiles demonstrated a reduction in differences relative to the control group during the initial and mid-swing phases. At the same time, the entire post-intervention profile remained shifted in the direction of internal rotation. This means that the post-intervention profile of hip rotation was associated with a reduced difference from the controls in selected portions of the cycle, but the established axial deviation was not eliminated. In clinical practice, this may indicate that hip rotation is a parameter partially amenable to locomotor training, but to a large extent also dependent on structural factors and long-term neuromuscular strategies [22,23]. This is significant because disorders in the transverse plane at the level of the hip affect the alignment of distal limb segments and the foot progression angle [24].

Within the knee joint, an interesting picture emerged regarding the relationship between shape similarity and the magnitude of absolute differences. In the frontal plane, the f_2 values were high across all comparisons, indicating the preservation of a similar temporal course of changes in the alignment of the shank relative to the thigh. At the same time, very high f_1 values showed that these profiles remained quantitatively different. The decrease in f_1 values in the KF2 versus CG comparison relative to KF1 versus CG can be interpreted as a partial reduction in deviation following therapy, but not as full normalization. This result suggests that robotic training may have improved the organization of limb loading and stability during stance, but was not sufficient to fully correct the frontal alignment of the knee. In this plane, the final effect likely depends not only on muscular control, but also on the alignment of the pelvis, foot, and the axis of the entire limb [25,26]. A comparable tendency has been reported following robot-assisted gait training in children with cerebral palsy, where improvements were observed particularly in hip joint kinematics and selected spatiotemporal gait parameters, although normalization of the gait pattern was not achieved [27].

A similar relationship was observed in knee rotation. High f_2 values indicated very great similarity in the shape of the profiles, while f_1 values remained clearly above the threshold of permissible differences. Following the intervention, a shift in the profile toward a more external alignment was visible, thus in the direction of the physiological pattern. Nevertheless, full approximation to the control group was not achieved. The obtained result has practical significance as it demonstrates that guided movement training can influence the rotational organization of the knee, but the extent of this change is limited. This is biomechanically understandable, as knee rotation remains functionally linked to hip rotation and foot alignment, and improvement in one segment without full correction of the remaining links in the kinematic chain typically does not lead to complete normalization [16,23,28].

In the case of the foot and ankle joint, the results were even more complex. In the frontal plane, a slight change toward the reference was visible, associated with the appearance of eversion and a reduction in the mean inversion alignment following the intervention. On the one hand, this may indicate somewhat better adaptation of the foot to the ground surface and reduced pattern rigidity. On the other hand, the increase in maximum inversion and the persistently high f1 values indicate that these changes were of limited scope. Moreover, in some portions of the cycle, the differences relative to the control group were slightly greater following therapy, which should be interpreted with caution. A partial transformation of the foot loading strategy seems more likely than an unambiguous improvement in its frontal plane function [22,28,29].

The least favorable picture was obtained for the foot progression angle. Although the profiles before and after the intervention were very similar to each other, this did not indicate an improvement relative to the norm. Both before and after therapy, a shift in the direction of internal rotation persisted, and following the intervention, the range of internal rotation even increased. This result suggests that this parameter was relatively resistant to the applied intervention. From a clinical perspective, this is a significant observation, as the foot progression angle is among the parameters particularly strongly dependent on the complex relationships between hip rotation, pelvic alignment, tibial torsion, and the local organization of the foot [30,31]. In such a situation, gait training alone, even when intensive and repetitive, may not be sufficient to achieve the desired effect if it is not accompanied by targeted work on rotational control or management addressing the structural component.

The totality of the results therefore indicates that the intervention using PRODRobot had more of an effect on organizing the movement profiles and partially reducing selected deviations than on achieving full normalization of the gait pattern. For some variables, the change toward the reference concerned primarily specific phases of the cycle rather than the entire profile. From a methodological standpoint, this is a valuable observation, as it confirms the validity of analyzing complete temporal profiles rather than relying exclusively on individual extreme values. Only such an approach allows one to demonstrate whether a change genuinely concerns the organization of movement over time or merely a shift in one selected feature [15,16,32,33].

The obtained results are consistent with the current body of literature on robot-assisted gait training in children with cerebral palsy. On the one hand, the advantages of such therapy are emphasized, particularly the large number of repetitions, the possibility of pattern standardization, and safe movement guidance [19]. Similarly, other exercise-based interventions have been shown to improve movement organization and reduce functional asymmetries without necessarily restoring normal movement patterns, indicating that motor rehabilitation often results in partial rather than complete biomechanical normalization [34,35]. On the other hand, meta-analyses and reviews indicate that the advantage over conventional training is not unequivocal, and the effect depends on the selection of therapy parameters, the baseline functional level, and which elements of gait are subjected to assessment [25,36,37]. In light of the presented data, it can be hypothesized that PRODRobot may be a useful tool for modifying selected aspects of the locomotor pattern, particularly those related to movement repeatability and partial reorganization of the profile in the transverse plane, while demonstrating lesser effectiveness with regard to parameters more strongly dependent on established axial and rotational deformations.

Limitations of the Study

The main limitation of the study was the small sample size and the loss of some participants, including the death of patients over the course of the project, reduced the inferential power and may have introduced selection bias. The course of the study was

also disrupted by the COVID-19 pandemic; the implemented lockdown and organizational restrictions prevented the full implementation of the planned procedure, which may have affected the completeness of the data and the comparability of measurements. Furthermore, the study group was clinically heterogeneous, and the analysis primarily covered kinematic parameters without parallel functional assessment or long-term follow-up, which limits the interpretation of the clinical significance and durability of the obtained effects. It should additionally be mentioned that the gait assessment was not blinded, so assessor expectancy cannot be excluded. The follow-up period itself was short: only measurements immediately post-intervention were obtained, hence the durability or retention of any changes remains unknown.

5. Conclusions

- Robot-assisted gait training using the PRODROBOT device was associated with changes in the kinematic gait profiles of children with neurological disorders; however, the degree of these changes varied between joints and between the frontal and transverse planes.
- The most favorable changes following the intervention were noted within the hip and knee joints in the transverse plane and partially in the alignment of the knee in the frontal plane, where a reduction in quantitative differences relative to the reference pattern was found.
- High values of the f2 index alongside simultaneously elevated f1 values in the majority of the analyzed pairs indicate that following therapy, similarity in the shape of the temporal profiles was achieved without full normalization of their absolute values relative to the control group.
- In the frontal plane of the foot, the changes following the intervention were of limited scope and did not allow for unambiguous confirmation of the normalization of the movement pattern.
- The foot progression angle did not improve following the intervention, and the persisting deviations in the transverse plane suggest that these parameters may be less amenable to short-term robot-assisted gait training.
- The obtained results indicate that therapy using PRODROBOT (a robotic gait trainer) may constitute a valuable component of gait rehabilitation; however, a more complete approximation to the reference pattern likely requires longer therapy or a combined approach targeted particularly at rotational and axial disorders of the lower limb.

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Data Availability Statement: The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding authors.

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