Original article
https://doi.org/10.18019/1028-4427-2025-31-2-194-201

Kinematic and kinetic features of an unaffected limb during walking in children with spastic hemiplegia

U.F. Mamedov✉**, T.I. Dolganova, L.V. Smolkova, A.O. Trofimov, O.I. Gatamov, D.A. Popkov**

Ilizarov National Medical Research Centre for Traumatology and Orthopedics, Kurgan, Russian Federation

Corresponding author: Ulvi F. Mammadov, ulvi.mamedof@gmail.com

Abstract

Introduction The study of the functional characteristics of the unaffected side of the musculoskeletal system in patients with spastic hemiparesis contributes to the development of various aspects of medical rehabilitation.

Objective To determine the features of compensatory and adaptive behavior of the limb not involved in the pathogenesis in children with hemiplegia during walking and their dependence on age and previous surgical interventions on the triceps surae.

Materials and methods Locomotor characteristics of 78 children under 16 years of age with spastic hemiplegia and motor disorders corresponding to levels I–II GMFCS (Gross Motor Function Classification System) were compared with 77 healthy peers. Based on age and the triceps surae lengthening surgery, all children were divided into 6 groups. Kinematic data were recorded using Qualisys 7+ optical cameras and KISTLER dynamometric platforms. The video material was analyzed using QTM and Visual3D programs, and statistical data processing was performed using Microsoft EXCEL-2013 and AtteStat 12.0.5.

Results In the unaffected limb of children with spastic hemiplegia, a flexion position in the limb joints was observed, while the kinematics of its ankle joint did not differ significantly compared to healthy peers. Moreover, movements in the joints of the unaffected limb in children with hemiplegia were performed at greater energy consumption, especially in the knee and hip joints, while the power characteristics in the ankle joints were statistically lower than in healthy peers.

Discussion Significant increase, in comparison with the norm, and redistribution of power locomotor characteristics, as well as an increase in the GPS indicator of the total joint kinematic variability of the limb not involved in the pathogenesis indicate exclusively the compensatory nature of its behavior. Compensatory behavior is also shown by increased flexion angles in the joints and the sagittal tilt of the pelvis, which posturally eliminate the difference in leg length. Rotational positions of the pelvis and the femur, apparently, also serve to maintain the orientation of the foot.

Conclusion Compensatory behavior of the unaffected limb in children with hemiplegia during walking is manifested in kinetic and kinematic activity. Power locomotor characteristics are significantly redistributed compared to the normal values. Power indicators in the knee and hip joints increase, but power characteristics in the ankle significantly decrease. According to the GPS index, the total joint kinematic variability significantly increases, and the joint flexion angles and sagittal pelvic tilt increase to compensate for the difference in leg height. The procedure of early surgical lengthening of the triceps surae did not have a significant effect on the motor characteristics of the uninvolved limb.

Keywords: gait analysis, children, spastic hemiplegia, kinematics, kinetics

For citation: Mamedov UF, Dolganova TI, Smolkova LV, Trofimov AO, Gatamov OI, Popkov DA. Kinematic and kinetic features of an unaffected limb during walking in children with spastic hemiplegia. *Genij Ortopedii*. 2025;31(2):194-201. doi: 10.18019/1028-4427-2025-31-2-194-201.

INTRODUCTION

Hemiparetic forms of cerebral palsy are usually characterized by preserved motor functions and the ability to move independently [1, 2, 3]. The incidence of spastic hemiplegia in the structure of cerebral palsy does not exceed 15.3 % [4, 5]. Types of non-severe motor impairments according to the Gross Motor Function Classification System [6] prevail: 87.8 % of GMFCS level I, 7.1 % of GMFCS level II.

Kinematic and kinetic disorders, orthopedic problems of spastic hemiplegia on the affected side have been described and classified quite well [7, 8, 9]. However, there are only a few publications devoted to biomechanical studies of the features of movements of the uninvolved lower limb during walking [10, 11, 12, 13]. Known changes in the range of movements in the sagittal plane, rotation features of pelvic movements are considered compensatory, reflecting the degree of dysfunction on the contralateral, affected limb [14, 15, 16, 17]. Nevertheless, publications indicate the occurrence of orthopedic disorders in the foot of the unaffected limb [18, 19, 20].

The study of the problems of locomotor disorders on both sides in patients with spastic hemiparesis should contribute to the development of various aspects of medical rehabilitation [21]. Moreover, it is unknown whether there is a change in the adaptive age-related mechanisms of the uninvolved limb, and the impact of early isolated operations to correct ankle contractures on the kinematic and kinetic parameters of the unaffected limb is also unclear.

Purpose To determine the features of compensatory and adaptive behavior of the limb not involved in the pathogenesis in children with hemiplegia during walking and their dependence on age and previous surgical interventions on the triceps surae.

MATERIALS AND METHODS

This study included pediatric patients with spastic hemiplegia who were scheduled for surgical treatment at our institution. All patients underwent preoperative examination in the gait analysis laboratory.

Inclusion criteria were age under 16 years (open growth plates), GMFCS levels I–II, spastic hemiplegia.

Exclusion criteria were diagnosis of spastic diplegia, level greater than GMFCS II, age under 5 years, 16 years and older, previous multilevel interventions.

The study groups were formed according to the age criterion (5–9 years old and 10–15 years old), as well as to the criterion of performing triceps lengthening or so-called percutaneous fibrotomies (fibromyotomies) at an early age.

During the examination, patients walked independently or holding one hand of a parent, barefoot, on a 7-meter long platform at their usual speed. Kinematic data were recorded by Qualisys 7+ optical cameras with passive marker video capture technology; synchronized with six KISTLER dynamometric platforms (Switzerland). The IOR model was used for marker installation. Kinematics and kinetics analysis was performed with QTM (Qualisys) and Visual3D (C-Motion) software with automated calculation of values [17].

For statistical data processing, Microsoft EXCEL-2013 and AtteStat 12.0.5 were used. Quantitative characteristics of sample populations are presented in tables as medians with a percentile distribution level of 25 % ÷ 75 %. Based on the number of cases in groups, nonparametric statistics with a significance level of $p \leqslant 0.05$ were used to process the results. The statistical significance of differences in indicators between comparison groups was determined using the unpaired Wilcoxon test.

Permission to conduct the study was obtained from the institution ethics committee (protocol dated 07.10.2022 No. 2(72)). The study conducted in accordance with the ethical standards of the Helsinki Declaration of the World Medical Association "Ethical Principles of Medical Research Involving Human Subjects" with amendments of 2000, "Rules of Clinical Practice in the Russian Federation" approved by Order of the Ministry of Health of the Russian Federation dated 19.06.2003 No. 266. Parents of the subjects, authorized relatives or employees of social institutions confirmed their consent to conduct the study and publish its results without identifying the individual.

The locomotor characteristics of 78 children under 16 years of age with spastic hemiplegia and motor impairments corresponding to GMFCS levels I–II were compared with the data of 77 healthy peers. Based on age and the triceps surae lengthening surgery, all children were divided into 6 groups:

Group 1: 21 patients (21 limbs); age range — 5–9 years, mean age (7.2 ± 1.5) years; triceps surae lengthening was not performed previously;

Group 2: 8 patients (8 limbs); age range — 5–9 years, mean age — (7.7 ± 2.0) years; triceps surae lengthening was performed;

Group 3: 25 patients (25 limbs); age range — 10–15 years, mean age — (13.9 ± 1.6) years; triceps surae lengthening was not performed;

Group 4: 24 patients (24 limbs); age range — 10–15 years, mean age (12.4 ± 1.9) years; triceps surae lengthening was performed previously;

Group 5: 38 children (76 limbs); age range — 5–9 years, mean age — (6.9 ± 1.7) years; no gait pathology;

Group 6: 39 children (78 limbs); age range — 10–15 years, mean age — (12.7 ± 1.9) years; no gait pathology.

RESULTS

The data of the spatial and temporal characteristics of walking and the gait profile score show significant differences in the parameters of the unaffected limb from healthy peers (Table 1). In addition, we observed a significant increase in the stride width in group 2 (children under 10 years old with triceps lengthening performed) from both non-operated peers and healthy ones.

Table 1

Spatial and temporal characteristics of walking, GPS

Parameter	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
GPS, limb	12 (9.7 ÷ 13.7)	11 (8.7 ÷ 13)	10.2 (8.9 ÷ 11.1)	12.1 (10.2 ÷ 14.2)	**8.3* (6.4 ÷ 9.7)**	**7.8* (6.6 ÷ 9.0)**
General walking speed, m/sec	0.95 (0.78 ÷ 1.05)	0.9 (0.88 ÷ 0.97)	0.97 (0.9 ÷ 1.05)	0.91 (0.77 ÷ 1.05)	1.07 (0.81 ÷ 1.18)	1.2 (1.12 ÷ 1.31)
Stride width, m	0.11 (0.09 ÷ 0.12)	**0.15[1] (0.13 ÷ 0.18)**	0.13 (0.11 ÷ 0.16)	0.14 (0.11 ÷ 0.16)	0.09 (0.07 ÷ 0.1)	0.1 (0.08 ÷ 0.12)
Stride length, m	0.45 (0.42 ÷ 0.52)	0.44 (0.4 ÷ 0.48)	0.51 (0.47 ÷ 0.55)	0.49 (0.42 ÷ 0.53)	0.5 (0.45 ÷ 0.53)	**0.62* (0.56 ÷ 0.67)**
Stride duration, sec	0.47 (0.42 ÷ 0.5)	0.46 (0.43 ÷ 0.51)	0.52 (0.48 ÷ 0.54)	0.51 (0.45 ÷ 0.55)	0.47 (0.44 ÷ 0.49)	0.52 (0.49 ÷ 0.55)
% of stance from gait cycle duration	63.8 (61 ÷ 65.7)	62 (59 ÷ 64)	64.2 (62.2 ÷ 65.6)	65.2 (63.7 ÷ 66.4)	61.1 (60.7 ÷ 62.2)	61.7 (60.8 ÷ 62.6)
% of swing from gait cycle duration	36.3 (34.3 ÷ 39.2)	37.9 (36.5 ÷ 40.5)	35.7 (34.4 ÷ 37.8)	35 (34 ÷ 36.9)	38.5 (37.9 ÷ 39.3)	38.3 (37.4 ÷ 39.2)

Notes: * — significant differences according to the Wilcoxon criterion ($p < 0.05$) between the groups of healthy children and the cerebral palsy groups of the corresponding age; [1] — significant differences according to the Wilcoxon criterion ($p < 0.05$) between groups 1 and 2.

Tables 2 and 3 present the lower limb kinematics indices in the compared groups. In group of children with spastic hemiplegia, we can detect a pronounced flexion in the hip and knee joints from the moment of initial contact to the midstance of the gait cycle and high values of the flexion angle in the hip joint in the swing phase. However, no differences in ankle joint kinematics were found in comparison with healthy peers. A significant difference in the angle of foot orientation relative to the motion vector between the groups of healthy children reflects the physiological mechanism of torsional development of the hip as the child grows. An important finding is an increase in the angle of rotational position and the range of pelvic rotation on the side of the uninvolved limb, given that these indices, which differ from the healthy population, are present in both groups and in all the studied age ranges.

The indicators of the moments of forces arising during movements in the joints, as well as the generated power of movements indicate an increased energy consumption of the uninvolved limb gait, especially in movements in the knee and hip joints (Table 4). Moreover, the generated power of movements in the ankle joints of the uninvolved limb in children with spastic hemiplegia is significantly lower than in peers without movement pathology.

Table 2

Kinematics of the ankle and knee joints

Parameter	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
Maximum foot flexion in stance	11.04 (5.7 ÷ 16.5)	12.2 (11.2 ÷ 15.9)	14.8 (13.0 ÷ 17.0)	18.7 (15.1 ÷ 21.95)	11.9 (9.7 ÷ 14.5)	13.3 (10.5 ÷ 16.0)
Maximum plantar flexion	−19.8 (−28.6 ÷ −12.0)	−11.6 (−14.3 ÷ −8.9)	−11.2 (−13.5 ÷ −7.6)	−9.5 (−13.8 ÷ −5.1)	−15.1 (−18.7 ÷ −10.9)	−13.4 (−16.9 ÷ −8.8)
Foot position in swing	4.8 (0.0 ÷ 10.7)	5.7 (5.5 ÷ 8.7)	8.3 (7.2 ÷ 12.3)	8.7 (5.98 ÷ 10.3)	5.6 (2.7 ÷ 8.1)	7.3 (5.2 ÷ 8.8)
Foot inversion, max	16.1 (11.3 ÷ 21.1)	17.7 (14.4 ÷ 22.3)	14.8 (11.2 ÷ 18.7)	17.1 (10 ÷ 23.96)	15.8 (11.8 ÷)	13.3 (8.7 ÷ 15.7)
Range	15.6 (12.7 ÷ 17.6)	15.7 (12.5 ÷ 17.3)	14.3 (12 ÷ 16.3)	15.1 (12.6 ÷ 17.7)	15.2 (12.4 ÷ 17.5)	13.3 (11.3 ÷ 15.5)
Hind-foot clearance, cm	16.8 (15.7 ÷ 17.7)	16.2 (15.4 ÷ 17.8)	18.2 (16.6 ÷ 19.7)	18.6 (16.8 ÷ 19.95)	17.5 (16.4 ÷ 18.5)	20.8 (19.0 ÷ 23.0)
Knee joint position at contact, °	15.6 (12.0 ÷ 18.4)	15.7 (11.7 ÷ 17.4)	14.5 (11.6 ÷ 17.4)	22.981 (18.0 ÷ 30.8)	**7.0* (2.7 ÷ 11.2)**	**7.1* (4.0 ÷ 9.6)**
Max knee flexion in stance, °	29.3 (21.2 ÷ 34.2)	27.8 (22.1 ÷ 35.3)	27.6 (24.0 ÷ 31.5)	32.5 (26.3 ÷ 39.8)	**19.8* (13.7 ÷ 26.7)**	**18.5* (14.7 ÷ 23.5)**
Min flexion angle in stance, °	5.9 (1.4 ÷ 10.9)	11.0 (7.4 ÷ 15.1)	9.4 (6.4 ÷ 12.3)	13.8 (10.1 ÷ 18.98)	6.4 (3.4 ÷ 10.3)	**5.0[2] (1.2 ÷ 8.7)**
Knee flexion in swing, °	62.4 (54.5 ÷ 68.3)	63.0 (58.5 ÷ 67.3)	63.6 (58.7 ÷ 69.5)	68.3 (58.7 ÷ 71.8)	64.5 (60.7 ÷ 69.1)	60.9 (57.4 ÷ 65.1)

Notes: * — significant differences according to the Wilcoxon test ($p < 0.05$) between the groups of healthy children and the groups of the corresponding age with cerebral palsy; [1] — significant differences according to the Wilcoxon test ($p < 0.05$) between groups 3 and 4; [2]— significant differences according to the Wilcoxon test ($p < 0.05$) between groups 4 and 6.

Table 3

Kinematics of the hip and pelvis

Parameter	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
Femur position at initial contact, °	36.5 (30.1 ÷ 44.1)	33.5 (28.9 ÷ 37.5)	36.7 (30.0 ÷ 41.6)	38.1 (33.9 ÷ 44.2)	**27.9[1] (20.6 ÷ 34.3)**	**24,5* (16,9 ÷ 29,7)**
Max hip extension, °	−10.4 (−13.6 ÷ −6.3)	−7.3 (−10.6 ÷ −6.5)	−7.0 (−10.9 ÷ −2.7)	−6.4 (−13.0 ÷ −1.8)	−14.0 (−21.4 ÷ −8.0)	**−14,1* (−20,95 ÷ −10,2)**
Max hip flexion in swing, °	39.1 (31.8 ÷ 45.0)	37.3 (34.9 ÷ 39.6)	38.2 (31.3 ÷ 44.4)	41.4 (35.3 ÷ 46.7)	30.8 (25.6 ÷ 36.8)	**26,6* (21,1 ÷ 31,1)**

Table 3 (Continuation)

Kinematics of the hip and pelvis

Parameter	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
Sagittal pelvic tilt, ° Max values/range	16.5 (12.3 ÷ 20.4) 9.1 (6.5 ÷ 10.6)	14.0 (11.4 ÷ 16.8) 8.1 (6.6 ÷ 8.9)	15.8 (11.4 ÷ 19.9) 8.0 (5.9 ÷ 9.3)	14.4 (11.6 ÷ 19.4) 9.7 (7.6 ÷ 12.6)	**7.8*** **(3.7 ÷ 12.7)** **4.8** **(4.2 ÷ 5.3)**	**6,5*** **(0,9 ÷ 10,2)** **4,2** **(3,4 ÷ 4,6)**
Frontal pelvis inclination, ° Max values/range	2.5 (0.5 ÷ 4.2) 8.97 (7.0 ÷ 10.4)	3.0 (1.9 ÷ 5.0) 7.3 (6.5 ÷ 7.7)	3.7 (1.9 ÷ 6.1) 7.9 (6.0 ÷ 9.1)	4.0 (1.4 ÷ 6.3) 7.8 (6.2 ÷ 9.1)	3.5 (2.5 ÷ 4.6) 7.1 (5.8 ÷ 8.2)	3,3 (2,0 ÷ 4,5) 6,9 (5,2 ÷ 8,2)
Pelvis rotation, ° Max values/range	21.6 (14.9 ÷ 26.3) 21.8 (16.9 ÷ 29.0)	20.95 (15.0 ÷ 26.8) 19.9 (18.2 ÷ 22.2)	17.8 (13.8 ÷ 21.4) 17.96 (14.3 ÷ 20.8)	18.0 (12.5 ÷ 25.7) 20.6 (16.4 ÷ 26.1)	**8.4*** **(5.5 ÷ 10.95)** **15.51** **(12.1 ÷ 18.8)**	**7,2*** **(5,2 ÷ 9,3)** **13,42** **(10,1 ÷ 15,1)**
Femur adduction, ° Max values/range	9.3 (4.7 ÷ 13.7) 17.8 (15.5 ÷ 18.8)	7.2 (5.4 ÷ 10.2) 15.2 (13.3 ÷ 16.95)	8.8 (5.3 ÷ 11.4) 14.5 (11.7 ÷ 16.5)	7.9 (6.6 ÷ 9.8) 15.5 (13.1 ÷ 17.95)	9.0 (6.6 ÷ 11.2) 13.3 (11.7 ÷ 14.9)	7,5 (5,7 ÷ 9,8) 11,5 (9,6 ÷ 13,4)
Femur rotation, ° Max values/range	11.2 (9.1 ÷ 15.4) 21.1 (17.0 ÷ 23.7)	4.8 (0.1 ÷ 11.5) 19.8 (16.5 ÷ 20.95)	6.2 (−1.7 ÷ 11.7) 21.8 (14.2 ÷ 28.6)	11.8 (5.5 ÷ 22.3) 23.7 (19.5 ÷ 27.3)	9.6 (3.5 ÷ 15.2) 17.3 (14.7 ÷ 19.6)	11,3 (7,5 ÷ 15,8) 16,8 (13,7 ÷ 20,2)
Foot orientation, ° Max values/ minimum values	15.6 (7.4 ÷ 21.1) −5.1 (−10.2 ÷ −0.8)	14.2 (7.1 ÷ 21.7) −4.8 (−11.5 ÷ 0.55)	5.2 (−0.7 ÷ 14.6) −12.5 (−17.2 ÷ −4.0)	10.3 (3.9 ÷ 15.4) −8.3 (−14.7 ÷ −2.1)	23.5 (21.0 ÷ 26.8) −11.3 (−14.95 ÷ −6.5)	**3,7[3]** **(−0,3 ÷ 7,8)** **−11,6** **(−16,2 ÷ −6,5)**

Notes: * — significant differences according to the Wilcoxon test ($p < 0.05$) between the groups of healthy children and the groups of the corresponding age with cerebral palsy; [1] — significant differences according to the Wilcoxon test ($p < 0.05$) between groups 1 and 5; [3]— significant differences according to the Wilcoxon test ($p < 0.05$) between groups 5 and 6.

Table 4

Torque, useful power

Parameter	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
Hip extension, N×m	0.94 (0.73 ÷ 1.18)	0.78 (0.57 ÷ 0.93)	0.87 (0.7 ÷ 0.98)	0.88 (0.64 ÷ 1.17)	**0.73[1]** **(0.55 ÷ 0.99)**	0.77 (0.58 ÷ 0.92)
Femur abduction, N×m	0.61 (0.6 ÷ 0.72)	0.56 0.47 ÷ 0.68)	0.76 (0.7 ÷ 0.88)	0.7 (0.59 ÷ 0.87)	0.67 (0.59 ÷ 0.71)	0.85 (0.76 ÷ 0.92)
Knee extension, N×m	0.66 (0.47 ÷ 0.79)	0.7 (0.42 ÷ 0.96)	0.66 (0.41 ÷ 0.84)	0.87 (0.61 ÷ 1.17)	0.51 (0.31 ÷ 0.68)	**0.65[2]** **(0.43 ÷ 0.87)**
Plantar flexion, N×m	1.02 (0.87 ÷ 1.22)	1.1 (0.95 ÷ 1.28)	1.2 (1.09 ÷ 1.36)	1.25 (1.05 ÷ 1.45)	1.08 (0.91 ÷ 1.22)	1.45 (1.32 ÷ 1.55)
Hip power, W/kg	0.44 (0.24 ÷ 0.71)	0.27 (0.06 ÷ 0.38)	0.45 (0.19 ÷ 0.62)	0.36 (0.19 ÷ 0.47)	**0.27[1]** **(0.04 ÷ 0.42)**	0.21 (0.03 ÷ 0.34)
Knee power, W/kg	−0.49 (−0.81 ÷ −0.12)	−0.86 (−1.27 ÷ −0.3)	−0.71 (−1.07 ÷ −0.39)	−0.87 (−1.13 ÷ −0.48)	**−0.54[3]** **(−0.8 ÷ −0.26)**	−0.69 (−0.90 ÷ −0.45)
Ankle power, W/kg	0.95 (0.56 ÷ 1.62)	1.1 (0.67 ÷ 1.99)	1.49 (1.09 ÷ 1.97)	1.84 (1.10 ÷ 2.43)	**1.8*** **(1.24 ÷ 2.26)**	2.3 (1.60 ÷ 2.81)
Total useful power, W/kg	0.86 (0.17 ÷ 1.35)	0.60 (0.13 ÷ 1.74)	1.23 (0.57 ÷ 1.89)	1.34 (0.83 ÷ 2.195)	1.53 (0.82 ÷ 2.01)	1.83 (1.23 ÷ 2.39)

Notes:* — significant differences according to the Wilcoxon test ($p < 0.05$) between the groups of healthy children and the groups of the corresponding age with cerebral palsy; [1] — significant differences according to the Wilcoxon test ($p < 0.05$) between groups 1 and 5; [2] — reliable differences according to the Wilcoxon criterion ($p < 0.05$) between groups 4 and 6; [3] — significant differences according to the Wilcoxon test ($p < 0.05$) between groups 2 and 5.

DISCUSSION

Limb movement pathology on the affected side in spastic hemiplegia have been studied and classified quite well [7, 8, 22, 23].

The results of studies of movements and orthopedic condition of the unaffected limb in spastic hemiplegia in children are reported only in several works [10, 11, 12, 13, 24]. However, there is a risk of developing orthopedic pathology on the neurologically unaffected side [18, 19, 20], and correction of length discrepancy requires intervention of the controlled growth technique on the healthy limb [25, 26, 27, 28].

Increased flexion angles in the knee and hip joints during the stance phase of the gait cycle and in the swing phase are known and well described. The authors believe that the development of an adaptation mechanism to compensate for the inequality in limb lengths can explain this kinematic feature [10, 24, 29]. Our studies have also revealed such a feature of articulation in the joints, despite the fact that there are no differences in movements in the ankle joint compared to peers without movement pathology. We also believe that greater flexion angles in the knee and hip joints and excessive sagittal tilt of the pelvis are a mechanism for compensating for the inequality in limb length, especially since it does not disappear even after the elimination of ankle contracture in the early age (group 2 of our study). At the same time, movements in the hip and knee joints were accompanied by increased values of the resulting moments of force and generated power, which reflects the high energy consumption of such an adaptation mechanism. As for the kinetics of ankle joint movements, in contrast to the data of Cimolin et al. [24] on the absence of differences with healthy children, we noted a decrease in the strength characteristics of articulation in the ankle joint compared to the healthy population. This difference in the studies can be explained by the small sample in the work of Cimolin et al., which complicates the interpretation of the results. We see an explanation for the phenomenon we discovered in the general decrease in the motor activity of such children due to neurological pathology, in contrast to the healthy population [30].

Rotational positions of the pelvis and hip, increased range of motion on the part of both the involved and unaffected limbs can be explained by compensatory mechanisms for maintaining the orientation of the foot close to the motion vector [11, 14, 15]. Our studies confirm this statement, especially since high values of pelvic and hip rotation are accompanied by deviation of the foot axis within the physiological norm.

Finally, we note that our study did not reveal changes in the motor status of the uninvolved limb between the groups without early surgical intervention and with lengthening of the triceps surae at an early age. Progression of torsional deformities occurred equally in both groups, and compensatory flexion position in the knee and hip joints was present in all four studied groups of children with spastic hemiplegia in all age categories.

We believe that changes in the kinematics and kinetics of the unaffected limb, being compensatory, reflect the degree of the pathology of movements on the affected side, and their dynamics can serve as an indicator of the success of treatment and/or progression of motor disorders.

The results and conclusions presented in this study should be considered in view of the cross-sectional nature of the study of groups unrelated to each other and without dynamic observation. A study of the treatment results after multilevel interventions in combination with limb length correction may confirm the hypothesis of a decreased expression of compensatory indicators of the kinematics of the unaffected limb.

CONCLUSION

Compensatory behavior of the unaffected limb in children with hemiplegia during walking is reflected in kinetic and kinematic activity. Power locomotor characteristics are significantly redistributed compared to the normal values. Power indicators in the knee and hip joints increase, but significantly decrease in the ankle joint. According to the GPS index, the total joint kinematic variability significantly increases, and the joint flexion angles and sagittal pelvic tilt increase to compensate for the difference in the limb height. The procedure of early surgical lengthening of the triceps surae did not have a significant effect on the motor characteristics of the unaffected limb.

Conflict of interest *None.*

Funding *None.*

Ethical review *Approval was obtained from the institutional ethics committee to conduct the study (protocol dated 07.10.2022 No. 2(72)).*

Informed consent *The parents of the subjects, authorized relatives or employees of social institutions confirmed their consent to conduct the study and publish the results without identifying the individual.*

REFERENCES

1. Liptak GS, Murphy NA; Council on Children With Disabilities. Providing a primary care medical home for children and youth with cerebral palsy. *Pediatrics*. 2011;128(5):e1321-1329. doi: 10.1542/peds.2011-1468.
2. Patel DR, Neelakantan M, Pandher K, Merrick J. Cerebral palsy in children: a clinical overview. *Transl Pediatr*. 2020;9(Suppl 1):S125-S135. doi: 10.21037/tp.2020.01.01.
3. Michael-Asalu A, Taylor G, Campbell H, Lelea LL, Kirby RS. Cerebral Palsy: Diagnosis, Epidemiology, Genetics, and Clinical Update. *Adv Pediatr*. 2019;66:189-208. doi: 10.1016/j.yapd.2019.04.002.
4. Mushta SM, King C, Goldsmith S, et al. Epidemiology of Cerebral Palsy among Children and Adolescents in Arabic-Speaking Countries: A Systematic Review and Meta-Analysis. *Brain Sci*. 2022 29;12(7):859. doi: 10.3390/brainsci12070859.
5. Gorter JW, Rosenbaum PL, Hanna SE, et al. Limb distribution, motor impairment, and functional classification of cerebral palsy. *Dev Med Child Neurol*. 2004;46(7):461-467. doi: 10.1017/s0012162204000763.
6. Palisano RJ, Hanna SE, Rosenbaum PL, et al. Validation of a model of gross motor function for children with cerebral palsy. *Phys Ther*. 2000;80(10):974-985. doi: 10.1093/ptj/80.10.974.
7. Winters TF Jr, Gage JR, Hicks R. Gait patterns in spastic hemiplegia in children and young adults. *J Bone Joint Surg Am*. 1987;69(3):437-441.
8. Rodda J, Graham HK. Classification of gait patterns in spastic hemiplegia and spastic diplegia: a basis for a management algorithm. *Eur J Neurol*. 2001;8 Suppl 5:98-108. doi: 10.1046/j.1468-1331.2001.00042.x.
9. Wagenaar RC, Beek WJ. Hemiplegic gait: a kinematic analysis using walking speed as a basis. *J Biomech*. 1992;25(9):1007-1015. doi: 10.1016/0021-9290(92)90036-z.
10. Eek MN, Zügner R, Stefansdottir I, Tranberg R. Kinematic gait pattern in children with cerebral palsy and leg length discrepancy: Effects of an extra sole. *Gait Posture*. 2017;55:150-156. doi: 10.1016/j.gaitpost.2017.04.022.
11. Salazar-Torres JJ, McDowell BC, Kerr C, Cosgrove AP. Pelvic kinematics and their relationship to gait type in hemiplegic cerebral palsy. *Gait Posture*. 2011;33(4):620-624. doi: 10.1016/j.gaitpost.2011.02.004.
12. Vitenson AS, Petrushanskaya KA, Gritsenko GP et al. Biomechanical and neurophysiological foundation of application of phase electrical stimulation of muscles in children with hemiparetic form of infantile cerebral palsy. *Russian journal of biomechanics*. 2016;20(2):150-167. doi: 10.15593/RZhBiomeh/2016.2.05.
13. Park KB, Park H, Park BK, et al. Clinical and Gait Parameters Related to Pelvic Retraction in Patients with Spastic Hemiplegia. *J Clin Med*. 2019;8(5):679. doi: 10.3390/jcm8050679.
14. Wren TA, Lening C, Rethlefsen SA, Kay RM. Impact of gait analysis on correction of excessive hip internal rotation in ambulatory children with cerebral palsy: a randomized controlled trial. *Dev Med Child Neurol*. 2013;55(10):919-925. doi: 10.1111/dmcn.12184.
15. Hara R, Rethlefsen SA, Wren TAL, Kay RM. Predictors of Changes in Pelvic Rotation after Surgery with or without Femoral Derotational Osteotomy in Ambulatory Children with Cerebral Palsy. *Bioengineering (Basel)*. 2023;10(10):1214. doi: 10.3390/bioengineering10101214.
16. Min JJ, Kwon SS, Kim KT, et al. Evaluation of factors affecting external tibial torsion in patients with cerebral palsy. *BMC Musculoskelet Disord*. 2021;22(1):684. doi: 10.1186/s12891-021-04570-5.
17. Riad J, Finnbogason T, Broström E. Anatomical and dynamic rotational alignment in spastic unilateral cerebral palsy. *Gait Posture*. 2020;81:153-158. doi: 10.1016/j.gaitpost.2020.07.010.
18. Joo S, Miller F. Abnormalities in the uninvolved foot in children with spastic hemiplegia. *J Pediatr Orthop*. 2012;32(6):605-608. doi: 10.1097/BPO.0b013e318263a245.
19. Yoon JA, Jung DH, Lee JS, et al. Factors associated with unaffected foot deformity in unilateral cerebral palsy. *J Pediatr Orthop B*. 2020;29(1):29-34. doi: 10.1097/BPB.0000000000000665.
20. Allen PE, Jenkinson A, Stephens MM, O'Brien T. Abnormalities in the uninvolved lower limb in children with spastic hemiplegia: the effect of actual and functional leg-length discrepancy. *J Pediatr Orthop*. 2000;20(1):88-92.

21. Reid LB, Rose SE, Boyd RN. Rehabilitation and neuroplasticity in children with unilateral cerebral palsy. *Nat Rev Neurol*. 2015;11(7):390-400. doi: 10.1038/nrneurol.2015.97.
22. Riad J, Haglund-Akerlind Y, Miller F. Classification of spastic hemiplegic cerebral palsy in children. *J Pediatr Orthop*. 2007;27(7):758-764. doi: 10.1097/BPO.0b013e3181558a15.
23. Pinzur M. S. Gait patterns in spastic hemiplegia in children and young adults *J Bone Joint Surg Am*. 1987;69(8):1304.
24. Cimolin V, Galli M, Tenore N, et al. Gait strategy of uninvolved limb in children with spastic hemiplegia. *Eura Medicophys*. 2007;43(3):303-10.
25. Corradin M, Schiavon R, Borgo A, et al. The effects of uninvolved side epiphysiodesis for limb length equalization in children with unilateral cerebral palsy: clinical evaluation with the Edinburgh visual gait score. *Eur J Orthop Surg Traumatol*. 2018;28(5):977-984. doi: 10.1007/s00590-017-2097-3.
26. Fatkhulislamov RR, Gatamov OI, Mamedov UF, Popkov DA. Assessment of the state of patients with spastic cerebral palsy at transition to adult medical institutions: a cross-sectional study. *Genij Ortopedii*. 2023;29(4):376-381. doi: 10.18019/1028-4427-2023-29-4-376-381.
27. Demirel M, Sağlam Y, Yıldırım AM, et al. Temporary Epiphysiodesis Using the Eight-Plate in the Management of Children with Leg Length Discrepancy: A Retrospective Case Series. *Indian J Orthop*. 2022;56(5):874-882. doi: 10.1007/s43465-021-00599-9.
28. Tirta M, Hjorth MH, Jepsen JF, et al. Are percutaneous epiphysiodesis and Phemister technique effective in the treatment of leg-length discrepancy? A systematic review. *J Pediatr Orthop B*. 2024. doi: 10.1097/BPB.0000000000001160.
29. Liu XC, Fabry G, Molenaers G, et al. Kinematic and kinetic asymmetry in patients with leg-length discrepancy. *J Pediatr Orthop*. 1998;18(2):187-189.
30. Dolganova TI, Popkov DA, Dolganov DV, Chibirov GM. Indicators of the kinetics of locomotor stereotypes in healthy children in different speed ranges of movement. *Genij Ortopedii*. 2022;28(3):417-424. doi: 10.18019/1028-4427-2022-28-3-417-424.

The article was submitted 02.02.2024; approved after reviewing 02.08.2024; accepted for publication 05.02.2025.

Information about the authors:

Ulvi F. Mamedov — post-graduate student, ulvi.mamedof@gmail.com, https://orcid.org/0009-0008-0266-6515;

Tamara I. Dolganova — Doctor of Medical Sciences, leading researcher,
rjik532007@rambler.ru, https://orcid.org/0000-0002-0117-3451;

Lidiia V. Smolkova — post-graduate student, slv@odb45.ru, https://orcid.org/0000-0001-9665-0427;

Anatoly O. Trofimov — post-graduate student, a4texa@yandex.ru, https://orcid.org/0000-0003-3455-4530;

Orkhan I. Gatamov — Candidate of Medical Sciences, orthopaedic surgeon, Head of the Department,
or-gatamov@mail.ru, https://orcid.org/0009-0005-4244-5774;

Dmitry A. Popkov — Doctor of Medical Sciences, Professor of the Russian Academy of Sciences,
Corresponding Member of the French Academy of Medical Sciences, Head of the Clinic,
dpopkov@mail.ru, https://orcid.org/0000-0002-8996-867X.