Original article
https://doi.org/10.18019/1028-4427-2024-30-2-234-244

Gait analysis characteristic features in children with spastic hemiplegia

U.F. Mamedov✉, T.I. Dolganova, 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 There are not enough published studies on the impact of early isolated triceps lengthening operations in hemiparesis on the state of motor characteristics and on the development of orthopedic complications in children with GMFCS II.

Purpose Analyze motor locomotion in children with spastic hemiplegia who had not previously been operated on and those who had undergone isolated surgical lengthening of the triceps at an early age.

Material and methods Four groups of children with spastic hemiplegia according to Rodda et Graham types: I) type 2a gait (4 children), II) type 3 (3 children), III) type 4 (7 children), IV) type 4 with previous triceps lengthening (9 children).

Results The features revealed in gait types 2a, 3 and 4 in the sagittal plane correspond to the characteristic and previously described features. In all groups, asymmetric rotational movements of the pelvis and tilt asymmetry in the frontal plane were observed. In the group of early isolated tricep lengthening, a decrease in the moment of force by pushing with the foot at the end of the single-support phase was revealed, in combination with an increase in the moment of forces of knee joint extension in the single-support phase.

Discussion Early isolated triceps lengthening that weakens its function leads to a compensatory increase in the work of the knee extensors which is similar to the mechanism to of iatrogenic crouch gait, but does not result in a complete loss of walking function in the conditions of a contralateral healthy limb.

Conclusions Movement pathology is present in all three measurement planes in gait types 2a, 3, 4 according to the Rodda et Graham classification. The most pronounced deviations were found in gait type 3. The rotational turn of the pelvis is an initially compensatory mechanism due to intratorsion femur deformity. Isolated triceps lengthening surgeries performed at an early age lead to reduced plantar push strength, increased compensatory work of the knee extensors, and probably do not prevent the orthopedic pathology found in Rodda et Graham's gait type 4.

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

For citation: Mamedov UF, Dolganova TI Gatamov OI, Popkov DA. Gait analysis characteristic features in children with spastic hemiplegia. *Genij Ortopedii*. 2024;30(2):234-244. doi: 10.18019/1028-4427-2024-30-2-234-244

INTRODUCTION

The hemiparetic form of cerebral palsy is the most common variant of this disease [1]. Spastic hemiparesis is characterized by deficits in motor coordination, disorders of posture and balance, muscle weakness, spasticity, and insufficient selective control, present in the upper and lower limbs of one side of the body [2]. Despite such changes, almost all children develop the ability to walk independently without assistance [3, 4]. The main secondary orthopaedic disorders in spastic hemiplegia are contractures of the ankle, knee and hip joints, equinovarus or equinovalgus foot deformities, torsion deformities of the femur, and limb length discrepancy [5–7].

Computer gait analysis is necessary in most cases for diagnosing motion disorders and determining indications for surgical treatment [8, 9]. Recognized surgical approaches to correction of orthopaedic disorders are one-stage multilevel interventions that provide improvement in gait parameters over a follow-up period of more than 10 years [2, 10, 11]. However, isolated triceps lengthening at an early age of 4–6 years is considered an operation that has indications [3, 12], despite the fairly high rate of contracture recurrence which is associated with leg length discrepancy and poor function of the dorsal flexors [13].

The available classifications of gait disorders in spastic hemiplegia reflect the types of disorders and the general direction of the evolution of disorders as the child grows [3, 14, 15]. It is known that intensive conservative measures can improve the motor abilities of a child with GMFCS level I with spastic hemiparesis [2, 16].

However, there are insufficient literature sources on the effect of early isolated surgeries to lengthen the triceps surae for hemiparesis on the state of motor characteristics and the development of orthopaedic complications in children with GMFCS II level at an age corresponding to stages 2 and 3 of compensated orthopaedic changes (contractures and bone deformities) according to Graham et al. [16].

Purpose Analyze motor locomotion in children with spastic hemiplegia who had not previously been operated on and those who had undergone isolated surgical lengthening of the triceps at an early age.

MATERIALS AND METHODS

Inclusion criteria were age range of 9 up to 16 years, diagnosis of cerebral palsy, GMFCS II, spastic hemiparesis, no previous multilevel surgical interventions. Before surgery, all patients underwent 3D computer gait analysis.

Exclusion criteria were age 16 years and older, diagnosis of cerebral palsy, GMFCS III, spastic diplegia, previous multilevel surgical interventions.

The study groups were formed according to the clinical classification of gait, determined by visual control [3], and according to the criterion of triceps surae lengthening performed in an early age.

During the examination procedure, the patients walked independently or holding one hand of a parent, barefoot on a 7-meter path at their usual speed. Kinematic data was recorded by Qualisys 7+ optical cameras with passive marker video capture technology; synchronized with six KISTLER dynamometer platforms (Switzerland). The IOR model was used for setting markers. The analysis of kinematics and kinetics was carried out in the QTM (*Qualisys*) and Visual3D (*C-Motion*) programs with automated calculation of values [17].

For statistical data processing, the AtteStat 12.0.5 software was used. Given the small number of the sample, nonparametric statistics were used. Quantitative characteristics of indicators in sample populations were presented in tables in the form Me (25 ÷ 75 %), and the statistical significance of differences was determined using the unpaired Wilcoxon test for independent variables, accepting a significance level of $p \leqslant 0.05$.

To conduct the research, permission was obtained from the ethics committee at the Federal State Budgetary Institution Ilizarov National Medical Research Center for Traumatology and Orthopaedics, protocol No. 2 (72) dated 07.10.2022. The studies were conducted in accordance with the ethical standards of the Declaration of Helsinki of the World Medical Association "Ethical Principles for Scientific Medical Research Involving Human Subjects" as amended in 2000 and "Rules of Clinical Practice in the Russian Federation" approved by Order of the Ministry of Health of the Russian Federation dated June 19, 2003 No. 266. Parents of children participating in the study were present during the study and signed informed consent for its conduct and publication of research results without personal identification.

RESULTS

The following groups were formed from the total sample of 23 patients:

— Group I: type 2a according to Rodda et Graham: 4 subjects, aged 10 (9 ÷ 11.8) years, no previous surgery;

— Group II: type 3 according to Rodda et Graham: 3 subjects, aged 10 (9.5 ÷ 10) years, no previous surgery;

— Group III: type 4 according to Rodda et Graham: 7 subjects, aged 11 (9.25 ÷ 11) years, no previous surgery;

— Group IV: type 4 according to Rodda et Graham: 9 subjects, aged 11 (10 ÷ 14) years, triceps surae lengthening was performed at the age of 3–6 years. To lengthen the triceps, the methods of lengthening the Achilles tendon (3 cases) and percutaneous fibromyotomies (6 cases) were used.

Table 1 presents the spatiotemporal characteristics of walking and the integral index of the gait profile score (GPS).

Table 1

Spatiotemporal characteristics of walking, GPS

Parameter		Groups of patients			
		I	II	III	IV
GPS		9 (8.05 ÷ 10.78)	**13.6 (13.1 ÷ 17.8)[1]**	10.6 (8.7 ÷ 12.6)	13.5 (12.6 ÷ 17.2)
Speed; m/sec		1.01 (0.98 ÷ 1.05)	0.9 (0.89 ÷ 0.91)	0.84 (0.66 ÷ 0.98)	0.92 (0.77 ÷ 1.12)
Step width, m		0.11 (0.098 ÷ 0.13)	**0.16 (0.13 ÷ 0.17)[1]**	0.12 (0.07 ÷ 0.15)	0.15 (0.11 ÷ 0.19)
Step period length, m		1.08 (1.02 ÷ 1.09)	0.98(0.95 ÷ 0.99)	1.01 (0.08 ÷ 1.06)	0.99 (0.91 ÷ 1.08)
GPS	A	9 (8.05 ÷ 10.8)	**15.4 (15.35 ÷ 20.5)[1]**	**10.5 (8.9 ÷ 11.8)***	13.7 (11.7 ÷ 18.7)
	C	11.5 (11.1 ÷ 11.9)	10.7 (10.6 ÷ 13.1)	10.7 (8.8 ÷ 12.5)	12.8 (10 ÷ 13.9)
Step length; m	A	0.55 (0.52 ÷ 0.55)	0.49 (0.48 ÷ 0.49)	0.49 (0.39 ÷ 0.52)	0.49 (0.45 ÷ 0.52)
	C	0.53 (0.50 ÷ 0.53)	0.5 (0.5 ÷ 0.52)	0.52 (0.48 ÷ 0.54)	0.49 (0.44 ÷ 0.53)
Gait cycle time; sec	A	0.55 (0.50 ÷ 0.58)	0.61(0.59 ÷ 0.61)	0.58 (0.55 ÷ 0.68)	0.58 (0.55 ÷ 0.63)
	C	0.48 (0.44 ÷ 0.52)	0.5 (0.47 ÷ 0.5)	0.53 (0.48 ÷ 0.59)	0.51 (0.43 ÷ 0.55)
Stance phase, %	A	59.2 (56.7 ÷ 60.1)	57 (57 ÷ 57.8)	60.8 (59.7 ÷ 63)	59.9 (53.3 ÷ 61.1)
	C	62.1 (60.4 ÷ 63.3)	67 (65.5 ÷ 67.5)	64.4 (62.7 ÷ 69.9)	65.7 (64.1 ÷ 66.3)
Swing phase, %	A	41.3 (39.7 ÷ 44.3)	42 (41.9 ÷ 42.5)	39.2 (37 ÷ 40.6)	39.4 (38.7 ÷ 40.7)
	C	38.6 (37.1 ÷ 40.1)	33 (32.5 ÷ 34.6)	35.6 (33.1 ÷ 37.3)	34.3 (34.1 ÷ 36.1)

Note: A — affected limb, C — contralateral limb; * — significant differences according to the Wilcoxon test ($p < 0.05$) between groups III and IV; [1] — significant differences according to the Wilcoxon test ($p < 0.05$) between groups I and II

The significant differences in GPS found between the groups of gait types 2a and 3 rather indicate a natural evolution of motor disorders in increased severity of orthopaedic disorders, which is also reflected in step instability in the frontal plane. The differences between groups of gait types 4 (non-operated) and 4 (operated) are rather functional in nature, which is presented in more detail below. Tables 2, 3 and 4 show the features of the kinematics of the ankle, knee and hip joints in the sagittal plane and the moments of force.

Table 2

Ankle joint kinematics, N·m/kg

Parameter		Groups of patients			
		I	II	III	IV
Foot position at initial contact, °	A	**−6.2 (−13 ÷ −3.7)**	**−27.4 (−30.9 ÷ −26.7)**[1]	−8.2 (−10.2 ÷ −3.4)	−9.7 (−31.7 ÷ −8.4)
	C	6.8 (5.2 ÷ 8.5)	4.4 (3.2 ÷ 5.2)	5 (2 ÷ 5.5)	−0.3 (−3.2 ÷ 1.7)
Maximum dorsiflexion,°	A	−1.5 (−5.5 ÷ 3.5)	**−25 (−28.4 ÷ −24.5)**[1]	4.3 (−5.3 ÷ 6.8)	5.3 (−30.4 ÷ 11.0)
	C	19.1 (13.1 ÷ 23.3)	17 (16.1 ÷ 23)	17.7 (15.3 ÷ 20.6)	17 (13.4 ÷ 21.2)
Maximum plantar flexion,°	A	−12.2 (−19.3 ÷ −11.3)	**−36.7 (−46.9 ÷ −35.9)**[1]	−10.4 (−17.7 ÷ −6.9)	−14.2 (−20.2 ÷ −5.6)
	C	−11.2 (−17.5 ÷ −8.3)	−11.3 (−14.2 ÷ −8.7)	−11 (−20 ÷ −7.3)	−16 (−16.4 ÷ −12.3)
Ankle range of motion during gait cycle,°	A	15.5 (12.4 ÷ 20.9)	11.7 (11.4 ÷ 18.5)	15.3 (1.2 ÷ 20)	15.5 (13.7 ÷ 24.3)
	C	35.4 (29.6 ÷ 37.8)	34 (30.3 ÷ 34.5)	25.9 (23.7 ÷ 31.8)	31.9 (25.9 ÷ 40.5)
Step clearance at forefoot, cm	A	4.1 (3.8 ÷ 5.1)	4.9 (4.8 ÷ 5.2)	4.5 (3.9 ÷ 5.9)	5.3 (5 ÷ 5.5)
	C	5.3 (5.1 ÷ 5.7)	6 (5.8 ÷ 7.4)	5.5 (5.1 ÷ 6.3)	6.3 (5.5 ÷ 7.4)
Relative force moment of dorsiflexion, N·m/kg	F	0 (−0.01 ÷ 0.02)	0.007 (0.0065 ÷ 0.0075)	−0.006 (−0.023 ÷ −0.007)	−0.004 (−0.007 ÷ −0.002)
	C	−0.05 (−0.08 ÷ −0.02)	−0.104 (−0.105 ÷ −0.08)	−0.101 (−0.134 ÷ −0.076)	−0.056 (−0.075 ÷ −0.027)
Relative moment of plantar flexion, N·m/kg	A	0.84 (0.66 ÷ 1.02)	**0.47 (0.39 ÷ 0.48)**[1]	1.05 (0.92 ÷ 1.1)	**0.77 (0.4 ÷ 1.16)***
	C	1.3 (1.1 ÷ 1.4)	**1.43 (1.33 ÷ 1.46)**[2]	1.15 (1.07 ÷ 1.23)	1.32 (1.04 ÷ 1.36)

Note: A — affected limb, C — contralateral limb; * — significant differences according to the Wilcoxon test ($p < 0.05$) between groups III and IV; [1] — significant differences according to the Wilcoxon test ($p < 0.05$) between groups I and II; [2] — significant differences according to the Wilcoxon test ($p < 0.05$) between the affected (A) and contralateral limb (C)

Table 3

Kinematic and kinetics of the knee joint

Parameter		Groups of patients			
		I	II	III	IV
Knee position at initial contact, °	A	24.7 (22.5 ÷ 25.8)	30.1 (29.5 ÷ 40.7)	19.4 (12.4 ÷ 26.8)	22.3 (19.8 ÷ 29.8)
	C	24 (20.6 ÷ 28.6)	17 (15.5 ÷ 27.4)	24.5 (21.6 ÷ 28.4)	19.5 (18 ÷ 31)
Maximum extension, mid single support phase,°	A	9.3 (7.8 ÷ 11.5)	**27 (24.9 ÷ 27.6)**[1]	6.9 (4.8 ÷ 14.2)	10.8 (7.1 ÷ 28.8)
	C	17.4 (14.8 ÷ 20.3)	7.2 (5.4 ÷ 14.6)	11.8 (9.4 ÷ 13.3)	14.6 (10 ÷ 15.8)
Maximum flexion in swing phase,°	A	62.8 (61.5 ÷ 64.9)	54.8 (53.9 ÷ 66.5)	56.5 (52.7 ÷ 66.5)	52 (50 ÷ 59.2)
	C	72.3 (66.4 ÷ 75.1)	63 (61.7 ÷ 66)	61.5 (56.4 ÷ 67.2)	71.2 (65.7 ÷ 71.8)
Range of motion during gait cycle, °	A	50.9 (47.5 ÷ 57.2)	**26 (23.4 ÷ 26.3)**[1]	49.1 (43.9 ÷ 51.4)	**29.3 (27.8 ÷ 46.9)***
	C	54.6 (50.9 ÷ 55.6)	60.4 (58.6 ÷ 77)	48.6 (45.9 ÷ 56.6)	56 (50.4 ÷ 56.6)
Relative force moment of knee extension, N·m/kg	A	0.38 (0.32 ÷ 0.49)	**0.77 (0.7 ÷ 0.93)**[1]	0.3 (0.2 ÷ 0.41)	**0.69 (0.27 ÷ 0.71)***
	C	0.68 (0.59 ÷ 0.79)	1.35 (1.25 ÷ 1.38)	0.65 (0.53 ÷ 0.75)	0.97 (0.71 ÷ 1.17)

Note: A — affected limb, C — contralateral limb; * — significant differences according to the Wilcoxon test ($p < 0.05$) between groups III and IV; [1] — significant differences according to the Wilcoxon test ($p < 0.05$) between groups I and II; [2] — significant differences according to the Wilcoxon test ($p < 0.05$) between the affected (A) and contralateral limb (C)

Table 4

Kinematic s and kinetics of the hip joint

Parameter		Groups of patients			
		I	II	III	IV
Position at initial contact, °	A	33.1 (31.1 ÷ 36.15)	32 (31.6 ÷ 43.2)	28 (18.9 ÷ 33.8)	31.1 (30.4 ÷ 36.3)
	C	44.2 (37.3 ÷ 47.4)	43.3 (38.7 ÷ 47.9)	30.9 (30 ÷ 37.6)	35.4 (32 ÷ 41.8)
Maximum extension, single support phase, °	A	−3.7 (−4.4 ÷ −2.5)	**8 (7.6 ÷ 16.5)**[1,2]	−8.1 (−9.3 ÷ −3.7)	**2.7 (−5.2 ÷ 3.9)***
	C	−6.7 (−7.5 ÷ −3.8)	−11.0 (−12.5 ÷ −11.5)	−6.9 (−13 ÷ −6.3)	−10.1 (−13 ÷ −7.9)
Maximum flexion in a swing phase, °	A	39.3 (38.5 ÷ 41.6)	36 (35.9 ÷ 48.6)	31 (22.4 ÷ 41)	39 (30.9 ÷ 40.7)
	C	44.8 (39.03 ÷ 49)	41 (38.2 ÷ 51.5)	31.8 (30.9 ÷ 35.8)	39.6 (32.4 ÷ 42.7)
Maximum range of motion during gait cycle, °	A	42.6 (40.2 ÷ 46.5)	**29.9 (28.9 ÷ 33)**[1,2]	39.7 (34.4 ÷ 45.5)	36.1 (33.1 ÷ 42.9)
	C	47.6 (37.9 ÷ 57.7)	53.2 (49.8 ÷ 64.1)	37.8 (37.4 ÷ 46.5)	43.5 (40.2 ÷ 50.2)
Relative force moment of hip flexion, N·m/kg	A	−0.44 (−0.52 ÷ −0.35)	−0.34 (−0.49 ÷ −0.29)	−0.41 (−0.57 ÷ −0.31)	−0.46 (−0.53 ÷ −0.39)
	C	−0.42 (−0.52 ÷ −0.38)	−0.78 (−0.79 ÷ −0.75)	−0.4 (−0.63 ÷ −0.34)	−0.69 (−0.74 ÷ −0.66)
Relative force moment of hip extension, N·m/kg	A	0.76 (0.68 ÷ 0.81)	**0.94 (0.85 ÷ 1.195)**[1]	0.52 (0.45 ÷ 0.78)	**0.84 (0.66 ÷ 1.05)***
	C	0.75 (0.56 ÷ 0.97)	0.97 (0.96 ÷ 1.14)	0.63 (0.56 ÷ 0.79)	0.9 (0.85 ÷ 1.21)

Note: A — affected limb, C — contralateral limb; * — significant differences according to the Wilcoxon test ($p < 0.05$) between groups III and IV; [1] — significant differences according to the Wilcoxon test ($p < 0.05$) between groups I and II; [2] — significant differences according to the Wilcoxon test ($p < 0.05$) between the affected (A) and contralateral limb (C)

A clear difference in the parameters of ankle joint movements on the involved side is visible between gait types 2a and 3 in the data presented in Table 2: the limitation in the range of motion is carried out only in the plantar flexion sector at any moment of the gait cycle. This is precisely what explains the positive values of the moment of dorsal flexion forces, when there is practically no change in the position of the foot from the moment of initial contact to the middle of the single-support phase in gait type 3 (Fig. 1). We also note significant differences in the values of the moment of plantar flexion forces during concentric contraction between the healthy and involved limb in patients of the same subgroup, which is explained by the pronounced contracture of the triceps, characteristic of this situation, when the patient practically ceases to articulate in the ankle joint and moves bearing weight on the foot almost in a vertical position with a reduced overall range of motion (Fig. 1).

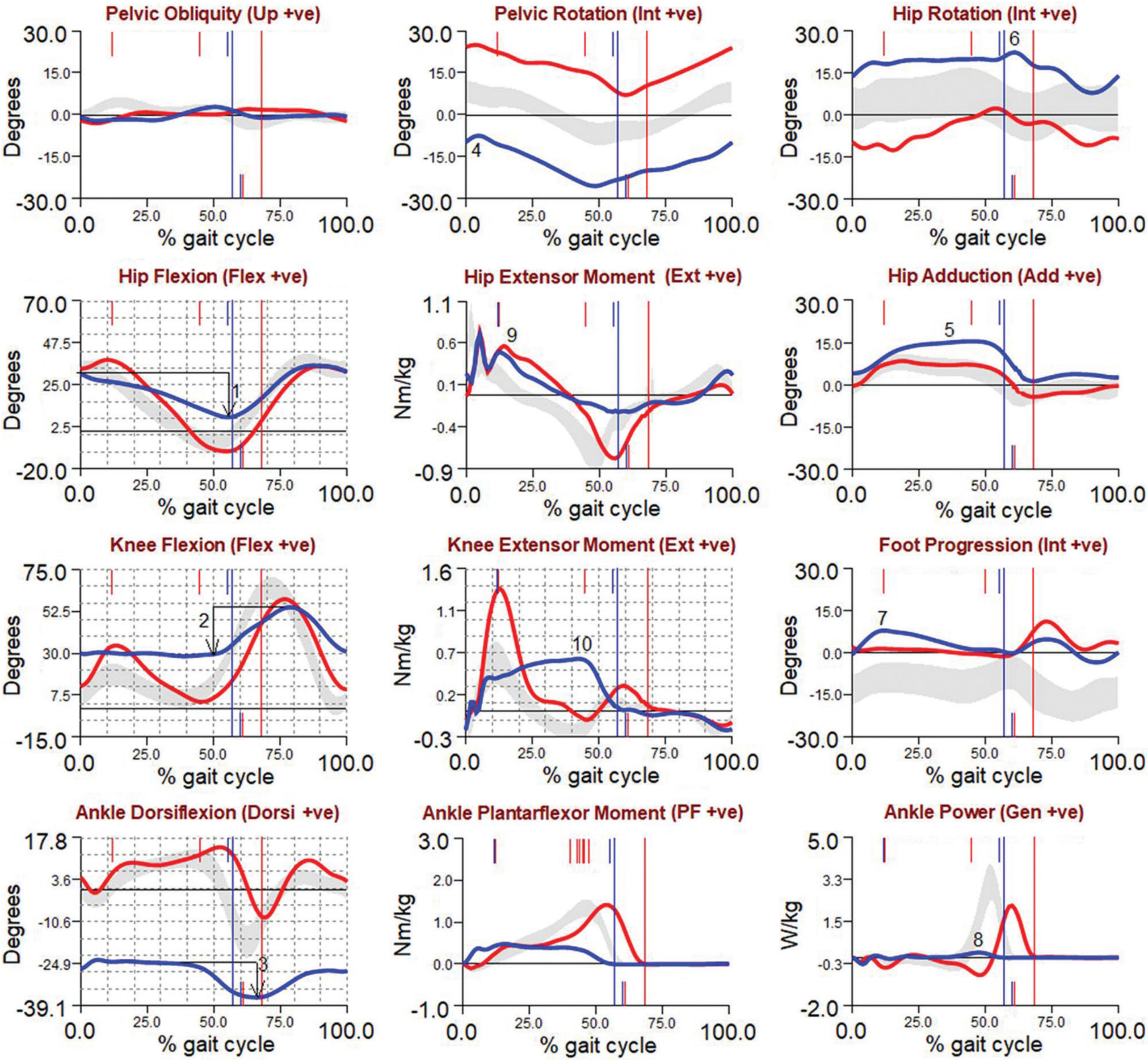

Fig. 1 Example of kinematic and kinetic diagrams of patient E (gait type 3), right-sided spastic hemiparesis (blue lines: involved limb): reduced range of motion in the hip (1), knee (2) and ankle joints (3) in the sagittal plane; these joints are in a flexion position (ankle: plantar flexion); typical pelvic tilt and compensatory rotation (4), moderate hip adduction during walking (5), pronounced torsion of the hip (6) and corresponding internal rotation of the foot (7) relative to the movement vector, reduced power characteristics of the plantar push (8), propulsion is carried out due to an increased moment of force during concentric contraction of the hip extensors (9), the work of the knee joint extensors (10) is aimed only at preventing further flexion in the knee joint in the support phase and can be characterized as an element typical of a stiff knee gait

An interesting finding is a significant decrease in the moment of plantar flexion in patients of group 4 (operated) in comparison with patients who have not previously been operated on (Fig. 2). It is obvious that after the operations performed there was no functional recovery. We also note the appearance of positive values of dorsal flexion in patients of groups 4 (operated). We explain these measurements by the formation of a plano-valgus abducted foot deformity (elevation of the forefoot) at this stage of the orthopaedic problems development, when in the sagittal plane, without taking into account the deviation, the foot is projected in a position of dorsiflexion.

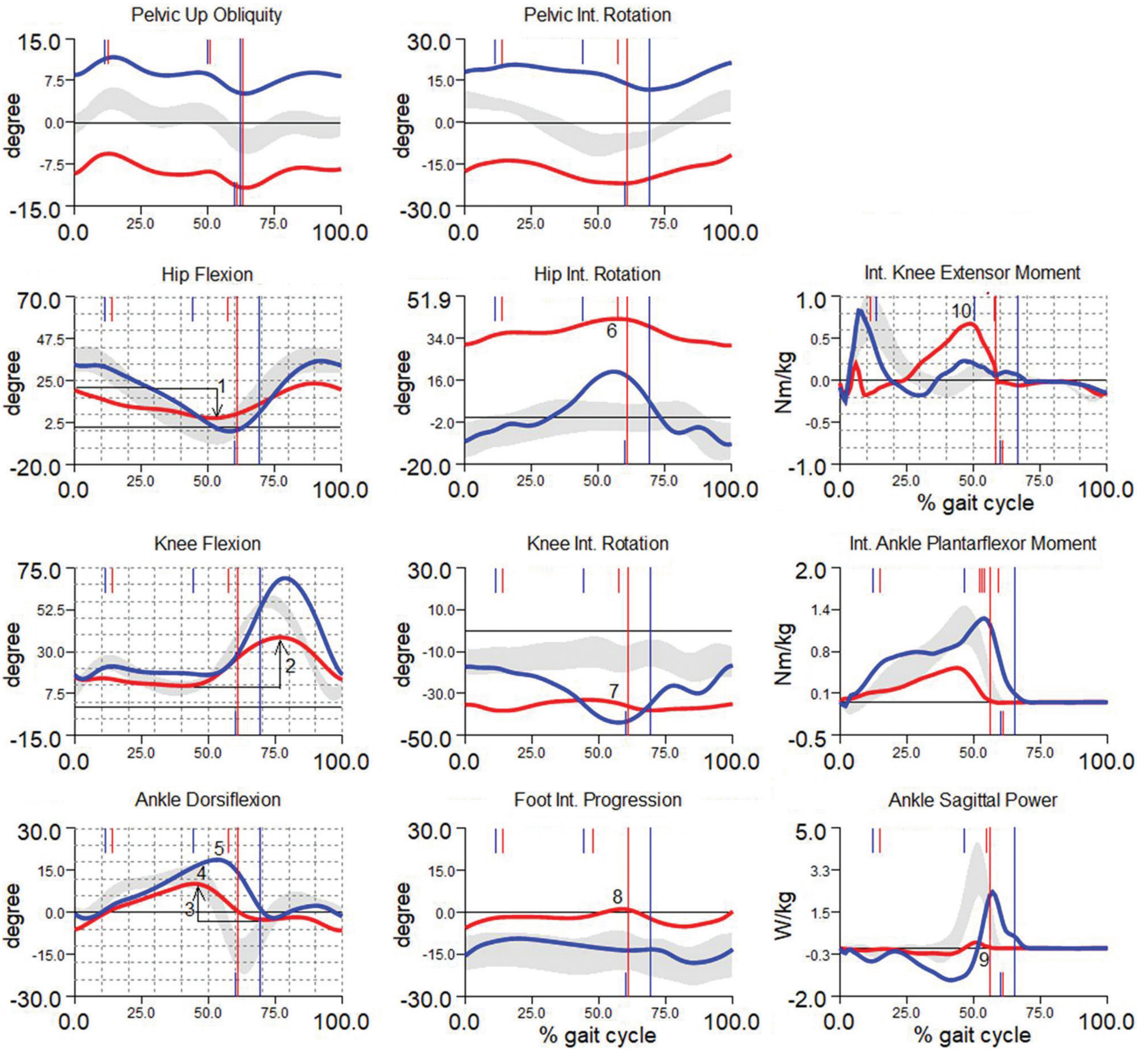

Fig. 2 Example of kinematic and kinetic graphs of patient V. (gait type 4, operative), left-sided spastic hemiparesis (red lines — involved limb): reduced range of motion in the hip (1), knee (2) and ankle joints (3) in the sagittal plane, the hip and knee joint are in a moderate flexion position, at the moment of the support phase there is sufficient dorsal flexion of the foot (4) and excessive (5) on the side not involved on the left, typical tilt of the pelvis and its compensatory rotation, pronounced intrarotational position of the hip (6) is partially compensated by external torsion of the lower leg (7), which is summarized by moderate internal rotation of the foot relative to the movement vector (8), reduced power characteristics of the plantar thrust (9), the work of the knee extensors is significantly increased relative to the uninvolved side (10) and compensates for weakness plantar flexors to maintain a sufficient angle of extension of the knee joint in the support phase, however, a sharp decrease in the amplitude of knee joint flexion in the non-support phase proves the formed compensatory element stiff knee gait

The flexion position of the knee joint in group III with a low range of motion throughout the entire gait cycle (compensatory stiff knee gait; Fig. 1) explains the increased moment of force of knee joint extension in comparison with group II. For group IV (Fig. 2), a significant decrease in the range of movements throughout the gait cycle, as well as increased values of the knee joint extension moment, reflect an adaptation mechanism in response to the weakened contractile function of the triceps surae.

A decrease in the overall range of motion in the hip joint due to its flexion contracture in the sagittal plane in patients with type 3 (Fig. 1) compared to type 2 leads to the need to increase the moment of extension forces to ensure propulsion (with concentric contractions of the hip extensors) at the end of the single-support gait phase (Table 4). The appearance of foot deformities that provide support not only on the forefoot allows patients of subgroups 4 and 4 (operated) to move with effective hip extension (Fig. 2). However, due to weakening of the triceps surae in patients in group 4 (operated), propulsion is provided not so much by plantar flexion as by extension in the hip joint, which is reflected in a significant difference in the values of the moment of extension forces in the hip joint.

Studies of pelvic and hip movements in the horizontal and frontal planes, as well as changes in the orientation of the common axis of the foot relative to the vector of movements, allowed us to go beyond the Rodda et Graham classification in understanding the kinematics of spastic hemiparesis (Table 5).

Table 5

Kinematics of the pelvis and femur in the frontal and horizontal plane, orientation of the common axis of the foot

Parameter	Limb		Groups of patients			
			I	II	III	IV
Pelvic obliquity, °	A	max	6.2 (4.8 ÷ 6.9)	3.1 (0.75 ÷ 3.5)	4.9 (2.33 ÷ 7.33)	3.5 (0.8 ÷ 6.3)
		min	−3.6 (−6.1 ÷ −1.8)	−3.4 (−4.5 ÷ −3.1)	−1.95 (−5.38 ÷ 0.18)	−3.1 (−5.4 ÷ 0.7)
	C	max	3.7 (1.9 ÷ 6.2)	2.1 (0.5 ÷ 2.3)	2.1 (−2.71 ÷ 4.95)	3.3 (−1.1 ÷ 4.9)
		min	−6.9 (−7.6 ÷ −5.3)	−7.1 (−9.3 ÷ −5.2)	−4.9 (−6.9 ÷ −2.05)	−3.2 (−8 ÷ −1.3)
Pelvic rotation, °	A	max	**9.2 (7.8 ÷ 9.6)[2]**	**4.1 (2.5 ÷ 5.2)[2]**	**1.1 (−4.7 ÷ 4.2)[2]**	**3.2 (−0.5 ÷ 9.1)[2]**
		min	−12.7 (−14.6 ÷ −11.8)	−22.7 (−24.3 ÷ −17.8)	−18.2 (−23 ÷ −14.6)	−18.1 (−21.8 ÷ −10.8)
	C	max	13.5 (12.1 ÷ 16.5)	26.4 (26.1 ÷ 26.7)	18.2 (15.6 ÷ 25.85)	22.9 (12.5 ÷ 26.8)
		min	−7.5 (−8.95 ÷ −6.03)	5.0 (0.9 ÷ 5.9)	−0.3 (−3.4 ÷ 6.15)	−1.2 (−5.4 ÷ 2.9)
Femur adduction, °	A	max	10.1 (7.4 ÷ 11.6)	4.9 (4.75 ÷ 5.15)	7.7 (0.05 ÷ 11.48)	8 (5.4 ÷ 10.9)
		min	−7.6 (−9.7 ÷ −5.4)	−7.8 (−9.7 ÷ −6.3)	−5.05 (−8.2 ÷ −2.65)	−4 (−10.5 ÷ −2.5)
	C	max	8.7 (7.7 ÷ 10.7)	9.3 (9.15 ÷ 9.5)	6.15 (4.75 ÷ 10.5)	7.3 (4.2 ÷ 8.6)
		min	−5.9 (−8.1 ÷ −4.9)	−8.6 (−10.2 ÷ −10.8)	−10 (−12.15 ÷ −4.8)	−10 (−12.6 ÷ −6.1)
Femur rotation, °	A	max	19.2 (12.5 ÷ 27.6)	**24.8 (23.9 ÷ 27.5)[2]**	19.6 (14.05 ÷ 23.2)	**21.2 (16.4 ÷ 30.1)[2]**
		min	−5.3 (−10.1 ÷ 1.95)	8.1 (7.8 ÷ 12.3)	−0.45 (−8.8 ÷ −4.8)	6.4 (0.3 ÷ 12.7)
	C	max	13.9 (12.5 ÷ 14.5)	9.1 (7.9 ÷ 18.9)	11.3 (7.23 ÷ 17.9)	6.1 (−2.7 ÷ 22.7)
		min	−8.6 (−13.3 ÷ 5.95)	−5.6 (−9.6 ÷ 0.45)	−15 (−19.5 ÷ −5.4)	−9.7 (−20.1 ÷ −3.1)
Foot orientation, °	A	max	4.9 (−2.3 ÷ 11.4)	11.0 (9.6 ÷ 24.9)	4.1 (−3.2 ÷ 14.2)	14.8 (7.2 ÷ 20.1)
		min	−16.5 (−19.2 ÷ −11.6)	−3.9 (−4.4 ÷ 2.3)	−15.0 (−20.2 ÷ −2.6)	−3.8 (−11.8 ÷ 6.1)
	C	max	13.1 (11.1 ÷ 14.2)	9.0 (8.7 ÷ 10.5)	3.3 (−5.05 ÷ 9.98)	7.0 (−0.2 ÷ 15.4)
		min	−4.45 (−9.8 ÷ −3.45)	−7.4 (−10.6 ÷ −5.5)	−12.9 (−20.6 ÷ −5.6)	−13.8 (−21.5 ÷ −1.9)

Note: A — affected limb, C — contralateral limb; [2] — significant differences according to the Wilcoxon test ($p < 0.05$) between the affected (A) and contralateral limb (C)

The movements of the pelvis in the frontal plane are identical and similar in amplitude in all subgroups: the predominant tilt of the pelvis towards the involved limb. Let us again note the decrease in the total amplitude of movements characteristic of the type 3 group. Even more demonstrative changes concern the kinematics of the pelvis in the horizontal plane. During the gait cycle, the rotation of the pelvis towards the involved limb dominates, which is significantly different from the uninvolved limb in all groups (Fig. 1 and 2), while the amplitude of pelvic rotation remains almost symmetrical between the involved and healthy limbs. During walking, the femur is evidently in the adducted position, with values significantly different from the uninvolved limb in groups 3 and 4 (operated). At the same time, the range of hip motion in the frontal plane in the patients of this study remains balanced.

Just like on average, there is orientation of the feet relative to the vector of movements. However, internal rotation of the foot of 15 degrees or more was observed in one patient in the type 3 group, two patients in the type 4 group, and four patients in the type 4 group (operated). This position is regarded as decompensation. In our sample, it was caused by torsion deformities of the femur in 4 cases and varus-supination deformity of the foot in three cases.

DISCUSSION

The first proposed classification of gait disorders in unilateral spastic lesions is that of Winters et al. [14], which distinguishes 4 groups based on the pathology of movements of the affected side limb in the sagittal plane. The classification reflects the progression of disorders from the distal level to the proximal level (from movement disorders in the ankle joint to the hip) as the severity of the disease increases. However, it was stated that the identified disorders cannot be determined according to this classification in 23 % of cases [15]. The Rodda et Graham classification is the most general and describes gait features in children with hemiparetic forms of cerebral palsy [3]. The classification reflects the progression of disorders from the distal level to the proximal level (from movement disorders in the ankle joint to the hip) as the severity of the disease increases.

Group 1 is characterized by an equinus position of the foot in the non-support phase of the gait cycle, the absence of the first rocker of the foot at the beginning of the support phase of the gait. The disorders are caused by weakness or underactivity of the tibialis anterior muscle in comparison with the gastrocnemius and soleus muscles. In group 2a, the foot is in an equinus position in the non-support phase of the gait cycle and in a constant plantar flexion; in group 2b, equinus contracture is observed in combination with recurvatum in the knee joint in the support phase. Group 2 disorders are caused by contracture of the triceps surae. In group 3, in addition to the above-mentioned disorders of groups 1 and 2, restriction of leg flexion at the knee joint in the non-support phase of the gait cycle and excessive flexion at the hip joint are added. In group 4 disorders, in addition to the previous disorders, there is a reduced range of motion in the hip and knee joints throughout the stepgait cycle and torsion deformities (pathological rotation of the hip). It should be noted that the classification does not consider lower limb discreapncy in assessing the severity of orthopaedic and motor disorders. We also did not find sufficient evidence in the literature that the progression of gait disorders correlates with the age of the child, as it is typical for spastic diplegia.

A number of additional studies based on computer gait analysis could clarify the features of movement of the foot, its anterior and posterior parts, which is important for choosing a method for correcting foot deformities and/or its intra-torsional position [18]. In addition to understanding the mechanism and elements of movement disorders in hemiparesis, 3D gait analysis enables to determine the level and magnitude of correction of deformities in the horizontal plane [7, 19, 20]. Our study also assists to distinguish torsion deformities (decompensated or compensated [34], there are mutually opposite directions at the level of the femur and lower leg) from foot deformities and determine the degree of necessary correction.

An important finding of our study is the identification of rotational turn in all studied subgroups of patients, which complements the description of gait features in the Rodda et Graham classification [3]. Rotational turn of the pelvis was previously considered as a pathological element caused by the topography of neurological lesions [21, 22]. Currently, torsional rotation of the pelvis is considered either as a result of spasticity and/or retraction of the muscles of the involved side, or as a compensatory mechanism that allows the axis of the foot on the side of the intratorsional deformation of the hip to be set in a more or less correct position relative to the movement vector [19, 23]. We believe that the presence of pelvic rotation in any of types 2–4 gait disorders found in our study is compensatory in nature, as it is combined with symmetrical amplitudes of pelvic movements on both sides. But as violations exist, this compensatory position becomes irreducible, which refers to tertiary violations [24–26]. We also point out that the following factors are associated with and determine the ineffectiveness of isolated surgical correction by the development of pathological rotational position of the pelvis: intratorsional deformity of the femur, Winter type 2 gait, limitations in dorsiflexion of the foot, anterior tilt of the pelvis and asymmetrical position of the upper limb from the side of the neurological lesion [27].

In our study, the most significant deviations in the total gait index (GPS) were observed in type 3. It is obvious that characteristic severe contractures restrict both the possibility of symmetrical support and a sufficient range of movements in the joints, reducing the strength characteristics of movements [2, 3, 8] . From this point of view, even greater impairments should be expected in type 4 according to Rodd et Graham. However, our study did not find such a hypothesized pattern. We hypothesize that the addition of a foot deformity that allows full support on this segment, and in the conditions of a healthy contralateral limb, improves the conditions for the implementation of movements in the knee and ankle joints of the involved limb.

We also note that in the group of patients who had triceps lengthened at an early age, we observe the presence of typical gait disorders for type 4, pathology of movements and orthopaedic disorders, as in the group of patients with the same type of disorders (type 4), but without orthopaedic operations . The only difference is a decrease in the contractility of the triceps for propulsion in combination with a compensatory increase in the moment of force of extension of the knee joint and the development of limited knee flexion in the swing phase (an element characteristic of stiff knee gait). This phenomenon of early isolated operations that weaken the triceps surae is characteristic of spastic diplegia [28, 29]. Obviously, this option of early operations does not lead to an improvement in the orthopaedic situation at an older age and only contributes to an increase in energy consumption for movement.

Limb length inequality in spastic hemiplegia is reflected in pelvic tilt, compensatory flexion of the hip and knee joints and conjugated dorsiflexion on the healthy side [31]. Our study also reflected these features, which emphasizes the importance of different leg length for the biomechanics of walking in hemiparesis. It is expected that correction of length discrepancy will avoid the involvement of a healthy limb in compensation for this orthopaedic pathology [32, 33].

The weaknesses of our study are its cross-sectional nature, without observing the evolution of gait pathology elements over time in children, without studying gait parameters before early orthopaedic operations. Another aspect that requires additional research is the study of adaptive changes in the movements of the contralateral limb, both in comparison with the involved limb and in comparison with healthy peers.

CONCLUSION

Pathology of movements detected by computer gait analysis is present in all three planes of measurements in gait types II, III, IV according to the Rodda et Graham classification. The most pronounced deviations in walking were identified in patients with gait type III.

Rotation of the pelvis is initially a compensatory mechanism caused by intratorsional hip deformation, allowing the axis of the foot to be oriented close to the walking direction vector.

Isolated triceps lengthening operations performed at an early age lead to a deterioration in gait parameters associated with a decrease in the force of the plantar impulse, an increase in the compensatory work of the knee extensors and the overall energy expenditure for walking and probably do not prevent the orthopaedic pathology that occurs in Rodda et Graham type IV gait.

Conflict of interest *None.*

Source of financing *The study was conducted within the framework of the topic "Use of computer gait analysis in substantiating the algorithm for orthopedic surgical treatment of patients with cerebral palsy" of the state assignment for the implementation of scientific research and development of the Federal State Budgetary Institution Ilizarov National Medical Research Center for Traumatology and Orthopedics of the Russian Ministry of Health.*

Ethical review *Not required.*

Informed consent *Not required.*

REFERENCES

1. Kulak W, Sobaniec W. Comparisons of right and left hemiparetic cerebral palsy. *Pediatr Neurol*. 2004;31(2):101-108. doi: 10.1016/j.pediatrneurol.2004.01.009
2. Bonnefoy-Mazure A, De Coulon G, Lascombes P, et al. A 10.5-year follow-up of walking with unilateral spastic cerebral palsy. *J Child Orthop*. 2023;17(2):173-183. doi: 10.1177/18632521231154975
3. 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
4. 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
5. Wren TA, Rethlefsen S, Kay RM. Prevalence of specific gait abnormalities in children with cerebral palsy: influence of cerebral palsy subtype, age, and previous surgery. *J Pediatr Orthop*. 2005;25(1):79-83. doi: 10.1097/00004694-200501000-00018
6. Romkes J, Hell AK, Brunner R. Changes in muscle activity in children with hemiplegic cerebral palsy while walking with and without ankle-foot orthoses. *Gait Posture*. 2006;24(4):467-74. doi: 10.1016/j.gaitpost.2005.12.001
7. Lee HJ, Oh CW, Song KS, et al. Rotational osteotomy with submuscular plating in skeletally immature patients with cerebral palsy. *J Orthop Sci*. 2013;18(4):557-62. doi: 10.1007/s00776-013-0384-3
8. Armand S, Decoulon G, Bonnefoy-Mazure A. Gait analysis in children with cerebral palsy. *EFORT Open Rev*. 2016;1(12):448-460. doi: 10.1302/2058-5241.1.000052
9. Chibirov GM, Dolganova TI, Dolganov DV, Popkov DA. Analysis of the causes of pathological patterns of the kinematic locomotor profile based on the findings of computer gait analysis in children with spastic CP types. *Genij Ortopedii*. 2019;25(4):493-500. doi: 10.18019/1028-4427-2019-25-4-493-500
10. Schranz C, Kruse A, Kraus T, et al. Does unilateral single-event multilevel surgery improve gait in children with spastic hemiplegia? A retrospective analysis of a long-term follow-up. *Gait Posture*. 2017;52:135-139. doi: 10.1016/j.gaitpost.2016.11.018
11. Gatamov OI, Chibirov GM, Borzunov DYu, et al. Correction of torsion deformities in adolescents and adults with cerebral palsy, impact on gait parameters. *Genij Ortopedii*, 2019, 25(4): 510-516. doi: 10.18019/1028-4427-2019-25-4-510-516
12. Sala DA, Grant AD, Kummer FJ. Equinus deformity in cerebral palsy: recurrence after tendo Achillis lengthening. *Dev Med Child Neurol*. 1997;39(1):45-48. doi: 10.1111/j.1469-8749.1997.tb08203.x
13. Sclavos N, Thomason P, Passmore E, et al. Foot drop after gastrocsoleus lengthening for equinus deformity in children with cerebral palsy. *Gait Posture*. 2023;100:254-260. doi: 10.1016/j.gaitpost.2023.01.007
14. 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.
15. Riad J, Haglund-Akerlind Y, Miller F. Classification of spastic hemiplegic cerebral palsy in children. *J Pediatr Orthop*. 2007;27(7):758-64. doi: 10.1097/BPO.0b013e3181558a15
16. Graham HK, Thomason P, Willoughby K, et al. Musculoskeletal Pathology in Cerebral Palsy: A Classification System and Reliability Study. *Children* (Basel). 2021;8(3):252. doi: 10.3390/children8030252
17. Aksenov A.Yu., Klishkovskaya T.A. *Program for the formation of a human walking biomechanics report*. Patent RF no. 2020665238. 2020. Available at: https://www.fips.ru/registers-doc-view/fips_servlet. Accessed Sept 14, 2023. (In Russ.)
18. Krzak JJ, Corcos DM, Damiano DL, et al. Kinematic foot types in youth with equinovarus secondary to hemiplegia. *Gait Posture*. 2015;41(2):402-408. doi: 10.1016/j.gaitpost.2014.10.027
19. Graham HK, Baker R, Dobson F, Morris ME. Multilevel orthopaedic surgery in group IV spastic hemiplegia. *J Bone Joint Surg Br*. 2005;87(4):548-55. doi: 10.1302/0301-620X.87B4.15525
20. Hamid J, Do P, Bauer J. 3D Gait Analysis and Patient-reported Outcomes of Femoral Osteotomies for Torsional Deformity. *J Pediatr Orthop*. 2022;42(9):496-502. doi: 10.1097/BPO.0000000000002204
21. Perry J. The mechanics of walking in hemiplegia. *Clin Orthop Relat Res*. 1969;63:23-31.
22. Siegfried J, Lazorthes Y, Broggi G, et al. La neurochirurgie fonctionnelle de l'infirmité motrice d'origine cérébrale [Functional neurosurgery of cerebral palsy]. *Neurochirurgie*. 1985;31 Suppl 1:1-118. (In French)
23. Park BS, Chung CY, Park MS, et al. Effects of soft tissue surgery on transverse kinematics in patients with cerebral palsy. *BMC Musculoskelet Disord*. 2019;20(1):566. doi: 10.1186/s12891-019-2955-8
24. Church C, Lennon N, Pineault K, et al. Persistence and Recurrence Following Femoral Derotational Osteotomy in Ambulatory Children With Cerebral Palsy. *J Pediatr Orthop*. 2017;37(7):447-453. doi: 10.1097/BPO.0000000000000701
25. Hosseinzadeh P, Baldwin K, Minaie A, Miller F. Management of Hip Disorders in Patients with Cerebral Palsy. *JBJS Rev*. 2020;8(3):e0148. doi: 10.2106/JBJS.RVW.19.00148
26. Sees JP, Truong WH, Novacheck TF, et al. What's New in the Orthopaedic Treatment of Ambulatory Children With Cerebral Palsy Using Gait Analysis. *J Pediatr Orthop*. 2020;40(6):e498-e503. doi: 10.1097/BPO.0000000000001461
27. 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

28. Dolganova TI, Gatamov OI, Chibirov GM, et al. Clinical and biomehanical results of multilevel orthopaedicinterventions in crouch-gait patients. *Genij Ortopedii*. 2020;26(3):325-333. doi: 10.18019/1028-4427-2020-26-3-325-333
29. Theologis T. Lever arm dysfunction in cerebral palsy gait. *J Child Orthop*. 2013;7(5):379-82. doi: 10.1007/s11832-013-0510-y
30. Dolganova TI, Dolganov DV, Chibirov GM, et al. Quantitative parameters of the kinetics and kinematics of the iatrogenic crouch gait pattern. *Genij Ortopedii*. 2022;28(5):675-683. doi: 10.18019/1028-4427-2022-28-5-675-683
31. 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.
32. 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
33. 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
34. Chibirov GM, Dolganova TI, Popkov DA, et al. Analysis of kinematic and kinetic parameters of pace in cerebral palsy patients with internal torsion hip deformity. *Siberian Scientific Medical Journal*. 2022;42(3):83–93. (In Russ.) doi: 10.18699/SSMJ20220311

The article was submitted 01.08.2023; approved after reviewing 08.09.2023; accepted for publication 24.02.2024.

Information about the authors:

Ulvi F. Mammadov — 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;

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

Dmitry A. Popkov — Doctor of Medical Sciences, Professor of RAS, correspondent member French Academy of Medical Sciences, dpopkov@mail.ru, https://orcid.org/0000-0002-8996-867X.