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Evolution of gait in preschool and primary school children after multilevel orthopedic surgeries performed to correct orthopedic complications of spastic diplegia

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Abstract

Introduction The optimal age for performing multilevel interventions in patients with cerebral palsy is the period from 10 to 16 years, but indications for eliminating contractures, torsional bone deformities, and foot deformities in children with cerebral palsy of GMFCS level I–III may also occur at an earlier age.

The **aim** of the work is to evaluate changes in the kinematic and kinetic parameters of gait in children with spastic diplegia who underwent multilevel bilateral surgical interventions for orthopedic complications of cerebral palsy that arose before the onset of pubertal growth acceleration.

Material and Methods 63 children with cerebral palsy, I–III GMFCS. Group 1 ($n = 50$): average age 7.1 years, no orthopedic interventions had been performed previously. Group 2 ($n = 513$): average age 7.4 years, isolated interventions were performed at the age of up to 4 years.

Results In group 1: after the operation for two years — an increase in the strength of all extensor muscles with a reliable difference compared to the preoperative level; after 4–5 years — stabilization of the achieved improvements in kinematics. In group 2: after the operation for two years — a decrease in the values of the total working power of the lower limb muscles; after 4 years — decompensation of motor capabilities occurred, the working power of the muscles of the hip and ankle joints did not exceed the initial values, and for the knee joint, the decrease in working power was permanent.

Discussion The positive effect of surgical intervention in both groups is similar and consists of improving the synergistic interaction of muscles.

Conclusion Orthopedic multilevel surgeries performed in children for orthopedic complications before prepubertal growth spurt are associated with functional development only in children who did not undergo early Achilles tendon lengthening or percutaneous fibromyotomies. The result remains stable for 4–5 years after surgery. Isolated Achilles tendon lengthening or percutaneous fibrotomies prevent lower limb muscular development in the long-term follow-up period.

Keywords: cerebral palsy, early-age multilevel surgery, instrumented gait analysis, long-term outcomes, children

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INTRODUCTION

Cerebral palsy (CP) is the most common cause of motor disorders in children (1.5–3 cases per 1,000 of pediatric population) [1, 2]. Conservative treatment (physical therapy, spasticity control, orthotic fitting) in children with global motor function impairment level I–III according to the Gross Motor Function Classification System (GMFCS) remains the method of choice until the age of six, when the development of muscle retractions (fixed contractures), bone deformities, and subluxations, as a rule, has not yet occurred [3, 4]. It has been established and repeatedly proven that the development of secondary orthopedic complications leads to both a decrease in motor activity and the loss of previously acquired skills and a significant deterioration in the quality of life, despite the stable nature of encephalopathy [5–10]. For surgical orthopedic correction of contractures, dislocations and bone deformities, the method of choice is simultaneous bilateral (or sequential bilateral with a short time interval) multilevel orthopedic interventions, accompanied by a single rehabilitation period [11–13]. Computer 3D gait analysis is a universal tool for assessing motor disorders, measuring orthopedic deformities and contractures, which are one of the factors in the deterioration of motor activity, quantitative planning of orthopedic intervention elements and the treatment outcome in subsequent years of monitoring the child [7, 14].

The optimal age for performing multilevel interventions is the period from 10 to 16 years old, especially the second half of the pubertal growth acceleration [15–17], when the risk of recurrence of orthopedic problems decreases [18]. However, indications for the elimination of contractures, torsional bone deformities, foot deformities in children with cerebral palsy of GMFCS levels I–III may also arise at an earlier age [5, 6, 9, 10, 19] if conservative therapy fails [20, 21]. Separately, it is necessary to point out the development of iatrogenic orthopedic problems with isolated and/or inadequate lengthening of the triceps surae [22–26]. Percutaneous, so-called minimally invasive fibromyotomies, selective muscle lengthening, especially those performed without correction of foot deformities [27, 28], inevitably lead to the manifestation of muscle weakness and the development of a crouch gait pattern in the medium and especially long term [29–31]. If plantar flexion weakens due to uncorrected foot deformities and contractures of the overlying joints, orthopedic surgery may be indicated.

The **aim** of the work is to evaluate changes in the kinematic and kinetic parameters of gait in children with spastic diplegia who underwent multilevel bilateral surgical interventions for orthopedic complications of cerebral palsy that arose before the onset of pubertal growth acceleration.

MATERIAL AND METHODS

This retrospective study included 63 patients with spastic cerebral palsy who underwent bilateral multilevel intervention to correct orthopedic complications of the underlying disease.

Inclusion criteria were age up to 10 years, the ability to undergo computer gait analysis within the established examination timeframes (before surgery, at intervals of 1–2 years, 2–3 years, 4–5 years after surgery), levels of global motor functions I, II, III GMFCS.

Exclusion criteria were more severe levels of GMFCS, incomplete (in terms of timing) instrumental gait analysis, age at the time of multi-level intervention of 10 years or above, orthopedic surgery performed on one anatomical area.

Out of 511 cases, 63 patients who fully met the inclusion criteria were selected for the study.

Based on surgical history, patients were included in two groups (Table 1):

— Group 1 (n = 50) were patients who had previous surgical intervention on the muscular apparatus of the lower limbs;

— Group 2 (n = 13) were patients who underwent isolated interventions on the triceps of the lower legs (lengthening of the Achilles tendon, so-called “minimally invasive” fibromyotomies).

Table 1

Characteristics of the groups

Group	Number of patients	Age, years	Gender				GMFCS					
			female		male		I		II		III	
			n	%	*n*	%	*n*	%	*n*	%	*n*	%
1	50	7.1 ± 1.57	19	38	31	62	4	8	25	50	21	42
2	13	7.4 ± 0.85	5	38	8	62	3	23	6	46	4	31

Immediately before surgery and during the late postoperative period, patients underwent clinical and radiographic examinations and computer gait analysis. Patients walked barefoot on a seven-meter treadmill at their usual speed, either independently or holding a parent's hand.

Kinematic data were recorded using Qualisys 7+ optical cameras with passive marker video capture technology, synchronized with six KISTLER (Switzerland) dynamometric platforms. The IOR model was used for marker placement. Kinematics and kinetics analysis was performed using QTM (Qualisys) and Visual3D (C-Motion) software with automated value calculation [32]. The functional asymmetry coefficient of symmetrical lower limb kinetic parameters was calculated using the formula: $Kac = (D-S)/(D+S) \times 100\ \%$, where D and S are values for the right and left lower limbs, respectfully.

AtteStat 12.0.5 was used for statistical data processing. The hypothesis of normal distribution was tested using the Shapiro-Wilk test. Given the number of cases in the groups and the lack of confirmation of the hypothesis of normal distribution, nonparametric statistics were used to process the results. Quantitative characteristics of the sample populations are presented in the table as the median with the percentile distribution level (Me 25 % ÷ 75 %) and the number of casess (n). The statistical significance of differences was determined using the unpaired Wilcoxon test, with a significance level of $p \leq 0.05$. The relationship between parameters was assessed using the Spearman correlation coefficient.

The research was approved by the Ethics Committee of the Ilizarov National Medical Research Center of Traumatology and Orthopedics. The study was conducted in accordance with the ethical standards of the World Medical Association's Declaration of Helsinki, "Ethical Principles for Medical Research Involving Human Subjects," as amended in 2000, and the "Rules for Clinical Practice in the Russian Federation," approved by Order No. 266 of the Russian Ministry of Health dated June 19, 2003. The parents of the children participating in the study were present during the study and provided informed consent for publication of the study results without identifying their children.

RESULTS

The only fundamental difference between the groups was the attempt to restore active plantar flexion and improve the functioning conditions of the extensor apparatus of the knee joint (Table 2).

The summarized spatiotemporal characteristics and the integral gait index are presented in Table 3. The data allow us to identify a trend toward improvement in the global assessment of kinematic gait parameters in both groups after surgery over a period of at least three years. Within one to two years, a decrease in walking speed and gait cycles per minute was noted. After an obvious period of adaptation of movements to new anatomical parameters, an improvement in the quantitative gait characteristics was noted in both groups within two to three years after surgery: an increase in walking speed and stance period length, a decrease in the duration of the double-support period. However, in Group 2 (triceps lengthening in the early age), decompensation of motor abilities occurred from year four which was manifested by a significant increase in the GPS (gait profile score), a decrease in walking speed, and an increase in the duration of the double-support period of the gait cycle compared to Group 1. In addition, in Group 2, BMI values significantly increased and exceeded the age norm.

Table 2

Distribution of surgical elements in patient groups

Elements of bilateral interventions	Group 1 (*n* = 50)		Group 2 (*n* = 13)	
	n	%	*n*	%
Aponeurotomy of the lumbar muscles	7	14	2	15
Lengthening of the adductor longus muscle	41	82	13	100
Elongation of the gracilis muscle	35	70	13	100
Lengthening the medial flexors of the knee joint	42	84	4	31
Patellar stabilization	–		3	23
Aponeurotomy of the gastrocnemius muscle (Strayer) with or without aponeurotomy of the soleus muscle	50	100	2	15
Hoke's percutaneous Achilles tendon repair	9	18	2	15
Subtalar arthroereisis according to Grice	32	64	11	85
Lengthening of the lateral column of the foot according to Evans	8	16	2	15
Tenodesis of the posterior tibial muscle	46	92	13	100
Correction of torsion deformity of the hip	10	20	4	31
Derotational varus osteotomy	3	6	2	15
Achilles tendon shortening	–		3	23

Table 3

Spatiotemporal characteristics of gait cycle and body mass index

Parameter	Group	Before surgery	After Surgery		
			1–2 years	2–3 years	4–5 years
Body mass index	1	15.9 (13.9÷17.3)	16.0 (14.4÷17.5)	16.8 (15.8÷18.4)	**16.7 (15.3÷17.6)**
	2	16.7 (13.5÷21.5)	16.3 (13.7÷17.3)	**19.1 (16.2÷23.8)**	**21.5 (18.1÷24.3)*1**
Gait index (GPS), °	1	17.0 (12.9÷21.2)	14.4 (11.6÷16.1)	13.7 (11.3÷14.6)	**11.9 (10.4÷12.6)**
	2	17.6 (14.2÷20.5)	15.6 (12.9÷17.8)	13.2 (11.5÷14.3)	**14.1 (13.4÷15.2)***
Speed, m/sec	1	0.56 (0.39–0.78)	0.53 (0.34–0.68)	0.65 (0.49–0.87)	**0.83 (0.68–1.01)1**
	2	0.71 (0.58÷0.86)	0.61 (0.36÷0.83)	0.71 (0.46÷0.95)	**0.59 (0.52÷0.66)***
Step period length, m	1	0.64 (0.51÷0.79)	0.64 (0.52÷0.71)	0.83 (0.72÷0.95)	0.94 (0.89÷1.07)
	2	0.78 (0.68÷0.88)	0.7 (0.56÷0.78)	0.83 (0.73÷0.96)	0.84 (0.77÷0.98)
Step width, m	1	0.14 (0.11÷0.16)	0.15 (0.12÷0.19)	0.15 (0.13÷0.19)	0.16 (0.13÷0.2)
	2	0.14 (0.11÷0.15)	0.15 (0.1÷0.18)	0.15 (0.12÷0.17)	0.16 (0.13÷0.18)
Gait cycles per min	1	51.3 (42.9÷61.6)	47.7 (37.1÷56.8)	46.3 (42.0÷55.9)	51.0 (45.7÷55.4)
	2	60.6 (52.9÷63.8)	50.7 (42.9÷55.4)	51.1 (38.8÷65.9)	42.2 (39.0÷43.9)
Duration of support period from gait cycle, %	1	67.0 (62.7÷71.2)	69.9 (65.2÷74.2)	66.5 (62.2÷70.3)	67 (62.5÷71.1)
	2	64 (60.8÷67.7)	69.2 (63.4÷74.8)	67.5 (63.4÷68.9)	67. 0 (65.7÷70.2)
Duration of swing period from gait cycle, %	1	33.0 (29.4÷37.3)	29.4 (25.9÷34.9)	33.5 (29.8÷37.9)	33.0 (28.9÷37.6)
	2	36.9 (32.6÷39.8)	30.9 (25.2÷36.6)	32.5 (31.1÷36.7)	30.9 (29.8÷34.2)
Duration of double support period from gait cycle, %	1	33.5 (25.1÷38.5)	39.2 (28.0÷45.3)	31.6 (22.5÷39.6)	30.4 (25.2÷30.5)
	2	28.3 (21.7÷37.8)	39.3 (26.6÷52.6)	36.1 (26.5÷39.5)	**40.0 (31.9÷40.8)***

Note: * — significant differences according to the criterion between groups 1 and 2 at this period of comparison after surgery; 1 — reliable differences within this group compared with the previous study period

Interestingly, a positive significant correlation was observed between BMI and GPS (r = 0.769) from four years after surgery in group 2 (Table 4).

Table 4

Dynamics of several kinematic parameters

Parameter	Group	Before surgery	After surgery		
			1–2 years	2–3 years	4–5 years
Position of foot at initial contact (Г0), °	1	**−9.8 (−20.0÷0.6)**	**0.78 (−3.5÷5.0)[1]**	2.5 (−1.6÷6.8)	3.0 (1.3÷4.8)
	2	**3.0 (−4.0÷10.3)***	0.9 (−3.8÷7.1)	1.49 (−0.2÷3.1)	−0.1 (−2.8÷2.2)
Maximum dorsiflexion in stance(Г2), °	1	**−0.21 (−1.1÷0.0)**	**12.0 (7.7÷16.1)[1]**	17.4 (10.9÷21.3)	12.8 (10.3÷17.2)
	2	**17.4 (12.4÷24.1)***	11.9 (7.2÷16.8)	15.8 (8.2÷23.9)	13.1 (3.4÷24.3)
Position of foot in swing phase (Г4), °	1	**−4.5 (−13.3÷−6.9)**	**9.8 (5.6÷15.5)[1]**	10.5 (4.8÷15.6)	10.0 (9.8÷13.2)
	2	**11.5 (5.2÷17.8)***	9.8 (5.7÷14.4)	14.2 (7.4÷19.7)	11.2 (6.5÷14.2)
Clearance (forefoot tip), cm	1	4.6 (3.2÷5.5)	5.1 (3.9÷5.7)	5.7 (4.5÷5.6)	6.1 (5.5÷6.9)
	2	6.3 (4.8÷5.9)	4.8 (3.6÷6.0)	6.2 (4.3÷8.1)	6.2 (4.8÷8.1)
Knee position at initial contact (K0),°	1	27.0 (19.5÷35.5)	17.5 (10.9÷23.8)	20.9 (15.3÷28.9)	17.8 (11.9÷20.3)
	2	36.5 (20.8÷48.5)	17.9 (4.4÷28.8)	17.5 (1.3÷31.5)	18.9 (6.7÷32.8)
Extension range in stance (K1–K2), °	1	26.6 (14.7÷28.8)	18.4 (12.2÷24.8)	18.1 (10.3÷22.1)	15 (11.6÷18.9)
	2	18.3 (16.3÷24.7)	16.2 (7.5÷28.9)	14.5 (5.8÷21.1)	20.2 (17.0÷24.1)
Maximum knee extension in stance (K2), °	1	8.5 (0.9÷19.5)	0.52 (−9.4÷9.6)	5.3 (−3.9÷12.7)	3.2 (2.6÷8.0)
	2	16.2 (8.9÷36.6)	2.1 (−5.6÷9.2)	6.6 (−5.5÷14.0)	5.2 (−6.6÷13.3)
Maximum knee flexion in swing phase (K3), °	1	61.5 (54.5÷69.7)	52.7 (44.2÷62.6)	51.2 (44.1÷56.1)	52.6 (47.8÷61.5)
	2	71.5 (59.6÷86.1)	50.8 (44.1÷60.3)	55.9 (47.5÷61.5)	57.9 (46.5÷72.1)
Hip position at initial contact (T0), °	1	35.4 (28.3÷42.8)	36.6 (28.0÷44.9)	38.1 (33.5÷41.2)	36.1 (31.2÷40.1)
	2	42.4 (38.7÷48.9)	35.2 (29.8÷37.2)	38.0 (23.2÷49.3)	34.9 (28.4÷43.7)
Maximum hip extension (T2), °	1	1.8 (−6.5÷6.8)	1.3 (−7.8÷10.3)	−2.0 (−5.4÷0.08)	**−3.1 (−7.5÷−0.85)**
	2	9.1 (3.9÷11.5)	0.13 (−4.2÷7.9)	3.6 (−8.7÷12.2)	**9.8 (5.2÷16.1)***
Hip range of motion in sagittal plane, °	1	9.2 (7.4÷11)	9.1 (7.05÷11.2)	10.1 (7.3÷11.2)	12.8 (8.6÷13.8)
	2	10.6 (10.1÷11.3)	11.2 (10.1÷12.9)	9.5 (7.9÷10.8)	9.3 (7.1÷10.1)
Hip rotation range, °	1	24.3 (19.7÷29)	25.0 (18.9÷32.4)	27.4 (18.8÷33.7)	29.5 (19.1÷38.6)
	2	33.2 (18.9÷49.3)	28.2 (23.5÷35.5)	27.4 (21.2÷32.5)	27.4 (24.7÷29.3)
Femur rotation range, °	1	19.5 (14.9÷22.7)	20.9 (15.6÷26.0)	22.5 (16.5÷29.2)	22.5 (17.7÷24.4)
	2	25.7 (16.5÷32.5)	28.0 (24.8÷32.5)	18.8 (14.5÷23.2)	21.4 (14.2÷24.7)
Knee motion range, °	1	54.0 (45.7÷64.0)	53.4 (47.9÷59.1)	49.9 (37.5÷52.4)	50.5 (43.3÷59.5)
	2	53.8 (28.8÷70.2)	50.6 (37.6÷59.3)	51.1 (44.9÷59.0)	53.0 (45.3÷56.0)
Foot motion range in the satittal plane, °	1	25.9 (16.7÷34.2)	23.0 (19.1÷27.7)	27.4 (22.6÷31.8)	25.2 (19.5÷29.4)
	2	30.5 (24.3÷37.4)	26.5 (22.4÷30.9)	25.4 (18.2÷31.3)	25.4 (18.1÷25.7)

Note: * — significant differences according to the criterion between groups 1 and 2 at this period of comparison after surgery; [1] — reliable differences within this group compared with the previous study period

The key differences in kinematic parameters between the groups before multilevel surgeries were in range of motion and foot position. In group 1, passive dorsiflexion was significantly limited due to triceps contracture. Furthermore, the increase in knee extension range during the stance phase in group 1 naturally reflects the jump knee gait pattern, typical for this age group. No significant differences were found between the groups after surgery, although by the end of the follow-up, group 2 showed a trend toward increased knee flexion range during the stance phase, accompanied by full extension by mid-stance. This trend, combined with a clear limitation of maximum hip extension, significantly different from group 1, which is adaptive in nature at this stage, reflects the onset of the crouch gait pattern. This observation logically correlates with a decrease in Gait Profile Score values. It should be noted that no differences were found between the groups at the end of the follow-up in the parameter of maximum pelvic tilt in the sagittal plane: 14.8° (10.2÷18.8) in group 1 and 17.5° (13.8÷21.4) in group 2.

Table 5

Dynamics of several kinetic parameters

Parameter	Group	Before surgery	After surgery		
			1–2 years	2–3 years	4–5 years
Hip extension power, Nm/kg	1	**0.62 (0.45÷0.72)**	0.64 (0.48÷0.74)	0.72 (0.59÷0.84)	**0.89 (0.77÷1.0)**[1]
	2	**1.08 (0.79÷1.43)***	0.89 (0.63÷0.94)	0.89 (0.73÷1.08)	0.87 (0.76÷0.96)
Knee extension power, Nm/kg	1	0.4 (0.25÷0.53)	0.33 (0.17÷0.43)	0.6 (0.36÷0.82)	**0.62 (0.54÷0.64)**[1]
	2	0.53 (0.28÷0.75)	0.39 (0.12÷0.59)	0.51 (0.17÷0.64)	0.41 (0.16÷0.62)
Plantar flexion power, Nm/kg	1	0.66 (0.5÷0.86)	0.65 (0.39÷0.79)	0.79 (0.66÷0.95)	**1.12 (0.94÷1.19)**[1]
	2	0.62 (0.56÷0.81)	0.68 (0.49÷0.89)	0.78 (0.61÷0.97)	0.95 (0.81÷1.09)
Total power generated at the hip joint level, W/kg	1	**1.51 (0.96÷1.75)**	1.43 (1.0÷1.67)	1.61 (1.14÷1.63)	1.75 (1.29÷2.03)
	2	**2.93 (1.82÷4.11)***	0.98 (0.3÷1.31)	1.95 (1.39÷2.18)	2.03 (1.39÷2.37)
Efficiency of muscle contractions at the hip joint level, %	1	70.6 (63.4÷78.6)	72.2 (64.0÷80.2)	73.1 (64.2÷76.1)	70.3 (64.6÷73.7)
	2	68.8 (62.8÷72.4)	70.2 (64.5÷78.8)	69.1 (63.2÷75.7)	66.4 (56.3÷74.6)
Total power generated at the knee joint level, W/kg	1	1.7 (0.96÷2.18)	1.56 (0.99÷2.14)	2.1 (1.11÷3.04)	2.15 (1.43÷2.46)
	2	2.5 (1.46÷3.13)	2.1 (0.97÷2.57)	1.89 (1.29÷2.34)	1.69 (1.26÷2.1)
Efficiency of muscle contractions at the knee joint level, %	1	39.0 (26.5÷52.5)	39.1 (31.2÷46.1)	40.3 (31.9÷50.0)	**41.9 (35.8÷48.9)**
	2	38.3 (32.3÷37.0)	39.0 (31.1÷47.1)	33.2 (23.6÷41.2)	**30.7 (21.9÷35.3)***
Total power generated at the ankle joint level, W/kg	1	1.46 (0.66÷2.01)	1.17 (0.58÷1.39)	1.66 (0.98÷2.05)	**2.39 (1.51÷2.75)**
	2	1.64 (1.05÷2.13)	1.28 (0.71÷1.83)	1.39 (0.99÷1.63)	**1.5 (0.93÷1.66)***
Efficiency of muscle contractions at the ankle joint level, %	1	53.7 (44.1÷63.7)	48.4 (35.0÷61.5)	56.9 (48.9÷64.9)	61.1 (52.2÷68.0)
	2	52.2 (47.4÷55.2)	48.5 (41.2÷57.7)	50.9 (42.4÷59.8)	53.9 (49.2÷63.2)
Total power of the lower limb muscles, W/kg	1	4.64 (2.81÷6.42)	4.15 (2.77÷5.28)	5.39 (3.59÷7.36)	6.26 (4.78÷7.14)
	2	6.08 (4.98÷7.02)	4.36 (3.11÷6.31)	5.22 (4.1÷5.91)	5.23 (3.93÷7.1)
The effectiveness of the total power of the lower limb muscles, %	1	55.1 (51.1÷61.5)	54.4 (50.5÷58.3)	53.5 (50.3÷59.1)	58.9 (57.7÷60.2)
	2	54.9 (47.2÷60.7)	54.0 (49.7÷58.2)	52.9 (46.3÷58.7)	51.6 (46.3÷57.2)
Functional asymmetry of the total power of the lower limb muscles, %	1	19.7 (12.9÷25.7)	14.6 (5.2÷22.1)	21.1 (10.9÷27.0)	**20.4 (11.6÷28.9)**
	2	18.3 (11.6÷24.9)	19.8 (8.6÷24.2)	12.2 (6.85÷17.4)	**5.8 (4.67÷7.85)***
Functional asymmetry of the total efficiency of the lower limb muscles, %	1	6.8 (2.2÷9.7)	6.6 (4.5÷8.7)	8.6 (6.3÷10.7)	4.0 (2.3÷3.9)
	2	10.9 (4.6÷15.8)	7.3 (3.4÷4.1)	7.95 (5.0÷7.7)	4.4 (2.5÷6.28)

Note: * — significant differences according to the criterion between groups 1 and 2 at this period of comparison after surgery; [1] — reliable differences within this group compared with the previous study period

Several significant findings can be highlighted. Significantly higher power characteristics of hip joint movements in group 2 before multilevel interventions reflect the dominance of these locomotion patterns in gait generation, while the role of plantar flexion remains diminished. In group 1 up to two years after surgery, an increase in the force of extension contractions was observed at all levels of the lower extremity biomechanic chain; significant differences emerged after four years compared to preoperative levels. In group 2, normalized muscle contraction force at the hip and knee extension level did not reach preoperative levels at any time point. However, at the ankle joint, an increase in plantar flexion torque values was observed in both groups.

More significant differences relate to the total generated contraction power. While a decrease in this indicator can be noted in both groups for all three joints within one to two years postoperatively, an increase exceeding baseline values was observed in the long-term follow-up only in group 1. In group 2, the increase in total power did not exceed baseline values for the hip and ankle joints, while for the knee joint, the decrease in extension power was constant throughout the follow-up period, becoming significantly lower than group 1 values after four years.

Absence of a decrease in contraction power efficiency in both groups during the observation period and a decrease in the asymmetry of power efficiency compared to the asymmetry of total power indicators at each study period for both groups should be noted. It reflects the synergistic interaction of muscles (adherence to the "optimal gait" rule) while maintaining compensation for motor impairments [34].

The results of the study of the dynamics in the total power of movements at the level of the knee and ankle joints are presented in Figure 1 and Figure 2.

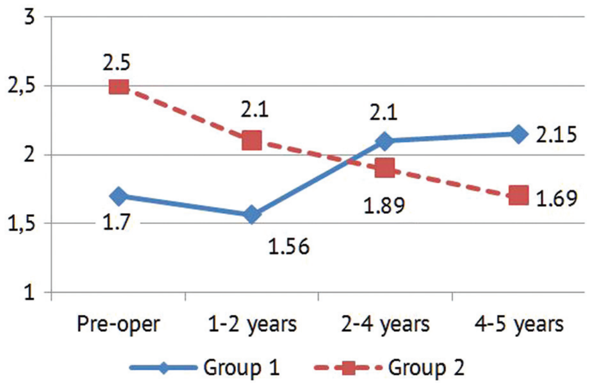

Fig. 1 Average values of total movement power at the knee joint level (W/kg) during follow-ups

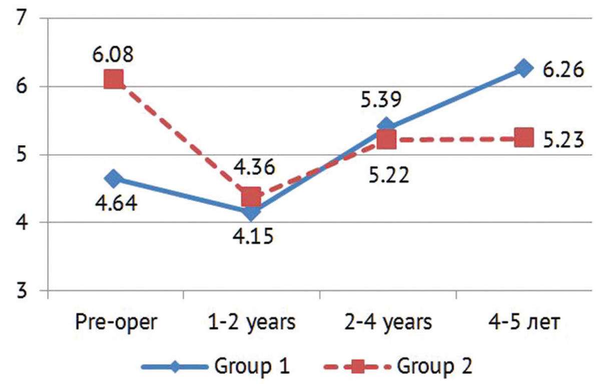

Fig. 2 Average values of total movement power at the ankle joint level (W/kg) during follow-ups

Finally, we would like to highlight the high positive correlation in group 1 between the "knee extension range of motion in the stance phase" and "knee extension power" parameters at two to three years and four to five years postoperatively: Spearman's coefficient was 0.600 and 0.691, respectively. For the "knee extension range of motion in the stance phase" and "knee extension power generation efficiency" pair, r = 0.501 and r = 0.483, respectively. This corresponds to sufficient functional capacity of the limb extension function. In group 2, the correlation coefficients for these pairs of parameters changed from positive (r = 0.115 and r = 0.430) to negative (r = –0.592 and r = –0.370) at two to three years postoperatively, reflecting a decrease in efforts and their efficiency for knee extension at the stance phase with an increase in the knee flexion range of motion. It is at this point that increased flexion in the hip joint becomes a compensatory mechanism at the onset of decompensation of the interconnected paired function of “knee extension” and “plantar flexion”.

The additional surgeries performed during the follow-up period were nine cases (18 %) in group 1, which included various combinations of the following:

— Repeated triceps surae lengthening (*n* = 2);

— Posterior tibial muscle tenodesis (*n* = 3);

— Evans foot reconstruction (*n* = 2);

— Adductor lengthening (*n* = 4);

— Patellar stabilization (*n* = 1);

— Correction of torsional deformities of the femurs (*n* = 3).

In Group 2, the following surgical procedures were performed on four patients:

— talonavicular arthrodeses (*n* = 3);

— posterior tibial muscle tenodeses (*n* = 3);

— correction of torsional deformities of the femurs (*n* = 1).

In most cases, the above-mentioned additional procedures were combined with the planned removal of osteosynthesis materials.

DISCUSSION

Multilevel bilateral orthopedic interventions in children with spastic diplegia who are able to walk independently (with or without assistive devices) are justified by the systemic nature of the disease, close timing of development of true orthopedic complications (contractures, bone deformities, dislocations/subluxations) and an integrated rehabilitation period [17, 33–35]. Baird et al. showed high correlation between the loss of achieved gait characteristics and the development of orthopedic deformities [5].

Graham et al. [6] distinguish two periods, coinciding in age (4–12 years) when orthopedic surgery becomes appropriate: the period of contractures and the period of bone deformations. During these periods, surgery is reconstructive in nature; it is possible to restore the anatomical parameters of the musculoskeletal system without performing elements of palliative interventions (arthrodesis).

It should be noted that before the development of orthopedic complications, treatment efforts in patients with cerebral palsy are aimed at developing their own motor abilities through the combined use of physical therapy [3], spasticity control, including botulinum therapy and selective dorsal rhizotomy [36, 37], and conservative methods for preventing contractures [38]. Unjustified premature orthopedic interventions on non-retracted muscles, even by increasing the passive range of motion in the joints, leads to their excessive weakening which is manifested by early functional decompensation and the development of iatrogenic crouch gait. A characteristic feature of iatrogenic crouch gait is its early age occurrence, even in the absence of torsional deformities [24, 31].

Multilevel interventions are usually performed at the age of 11–15 years (after pubertal growth acceleration) to achieve a stable surgical result [8, 17, 39, 40]. However, the authors note that in children over 12 years of age, it is often no longer possible to achieve complete anatomical restoration of the structures and relationships between limb segments and muscle proportions, and often the only solution is palliative orthopedic surgery for crouch gait [6]. Currently, there are conflicting recommendations regarding the optimal age of patients for reconstructive orthopedic interventions [3, 41, 42]. Svehlík et al. consider pubertal acceleration of lower limb growth as a factor in decompensation of motor capabilities and the development of the crouch gait pattern [18].

Performing orthopedic surgeries at an early age before the prepubertal growth spurt in children with cerebral palsy of GMFCS levels I–III is indicated in the case of early development of orthopedic complications of cerebral palsy (contractures of the ankle and knee joints, foot deformities, torsional deformities), which negatively affect the implementation of rehabilitation measures and orthotics, reducing the child’s motor abilities. The average age of performing early interventions in various series was: six years [40], 6.4 [43], 8.6 [6], 9.7 [44]. It is in the period from four to 12 years that a gradual decrease in the range of motion in the joints occurs and the role of muscle retraction increases compared to spasticity, the level of which gradually decreases [6]. Hägglund and Wagner found that 47 % of four-year-old children had spasticity of the gastrocnemius muscle of levels II–IV according to the Modified Ashworth Scale [45]. However, only 23 % of children at 12 years of age had their previous level of spasticity.

In our study, indications for multilevel interventions are due to both the early development of true orthopedic complications of cerebral palsy and the negative impact of isolated lengthening of the Achilles tendons or so-called “minimally invasive” early interventions, referred to as fibromyotomies, the negative effect of which is explained by a significant weakening of the strength of the plantar flexors of the foot with an increase in the amplitude of passive dorsiflexion [24, 31].

The positive impact of multilevel interventions on the kinematic and kinetic parameters of gait was discussed by many authors. The key effects in the immediate and mid-term postoperative periods are increases in step length, walking speed, and knee extension in the support phase, as well as a decrease in pelvic tilt and normalization and/or improvement of foot kinematics at each moment of the gait cycle. Rutz et al. note a change in GPS from 20.7° to 11.1° (by 47 %) towards gait normalization in the period from one to three years after surgery [17]. Dreher et al. state the maintenance of a significantly improved integral GPS indicator in the long-term period in 77 % of patients (177 out of 231 patients) and, at the same time, a decrease in GPS values in the first year after multilevel interventions [7].

Many researchers agree that the period of maintaining the positive effect of multilevel interventions is quite long. Godwin et al. [40], Thomason et al. [44] and Terjesen [8] describe the maintenance of the positive effect on gait parameters and the overall functional outcome in children with GMFCS levels II–III five years after bilateral intervention. In a multicenter retrospective study, Dreher et al. showed the maintenance of the achieved improved kinematic parameters nine years after multilevel interventions, when the age of the patients at the time of the last instrumental gait analysis was 19 years 8 months [7].

Our results are similar to those of the studies presented above. Orthopedic surgery improved ranges of motion in all planes in both groups throughout the entire follow-up period. Importantly, a temporary deterioration in kinematic parameters after surgery within one to two years was followed by a progressive improvement toward normalization. Differences between the groups were revealed four to five years after surgery when previously compromised plantar flexion in group 2 manifested itself as a significant increase in GPS, combined with a decrease in gait speed and an increase in BMI. In our study, we merely observed a correlation between these parameters without establishing a cause-and-effect relationship: movement impairment leads to a decrease in gait speed and an increase in body weight, or vice versa. We also note a significant restriction in maximum hip extension in group 2; this observation is interpreted in the discussion of kinetic parameters.

The authors note the need to perform individual additional surgeries (often combined with the removal of osteosynthesis material) to preserve the result of the primary intervention: Dreher et al. [7] in 39 % of cases, Tejersen et al. [8] in 48.3 %, Rutz et al. in 64.3 % [17]. At the same time, no statistically significant relationship was found between the incidence of additional interventions and parameters of gender, GMFCS level, previous surgeries, or age at surgery. In our series, the rate of unplanned surgeries aimed at preserving the results of the primary intervention is comparable to literature data.

The comprehensive treatment strategy for patients with cerebral palsy is based on the development of motor skills, functions, and improvement of gait parameters, as well as the prevention of secondary orthopedic complications, including walking with flexed knee joints (flexed-knee gait) which is a precursor to the crouch knee gait pattern when reconstructive treatment is impossible [3, 6, 10]. Moreover, the development or non-development of this pattern is considered a criterion for the effectiveness of the treatment [7, 8].

Therefore, we examine the results specifically from the perspective of identifying early signs of extension decompensation in the late period following surgical treatment that was necessarily performed at an early age in children with cerebral palsy of GMFCS levels I–III. It is important to emphasize the fundamental principle that improving motor abilities and gait parameters does not affect the GMFCS level caused by static encephalopathy [46].

We agree with the opinion of Hua et al. about the lack of studies that fully reflect the dynamics of kinetic parameters of gait after surgery, as well as the dynamics of kinematic data [47], given that the efficiency of energy expenditure for generating movements in children with cerebral palsy is 28 % lower than in healthy peers. The study of Van Rossom et al. confirms that multilevel interventions improve kinematic parameters, normalize moments of force at the level of the involved joints and improve the parameters of generated power of movements [48]. Considering the natural evolution of movement disorders in the direction of the crouch gait pattern [6, 9, 10], accompanied by extreme inefficiency of energy supply of gait, it is necessary to choose the methods for performing orthopedic interventions and subsequent rehabilitation that prevent such development of movement disorders. An obvious predictor of this unfavorable evolution, as clearly demonstrated by Pilloni et al., is the surgical weakening of the plantar flexors. Thereby, the first sign is an increase in the minimal flexion of the knee joint in the support phase [24].

Our results confirm the improvement in kinetic gait parameters after multilevel interventions in previously surgically intact patients: normalized hip, knee, and ankle extension moments increase, accompanied by an increase in the total power generated at these joints. In the long-term follow-up, total power exceeds baseline levels without losing its effectiveness. However, we observed a progressive decrease in knee and hip extension power in patients who underwent early triceps surae lengthening even if there was a progressive increase in plantar flexion power. Consequently, the total power generated at the knee and ankle joints was significantly higher in group 1 than in group 2. Similar to GPS values, a decrease in kinematic parameters was observed in both groups during a one- to two-year follow-up period. Another important difference is that while total power in group 1 was higher than preoperative after four to five years postoperatively, it never reached preoperative values in group 2. We also point to the predictor of extensor mechanism failure (hip extension deficit combined with excessive pelvic tilt in the sagittal plane), identified in our study and interpreted as a compensatory mechanism for the anterior displacement of the center of mass from the axis of knee joint motion. Nevertheless, the positive effect of surgery in both groups is similar and consists of a reduction in the asymmetry of total effectiveness relative to the asymmetry of total power. However, this is insufficient to maintain stable treatment results in patients predisposed to the development of the iatrogenic crouch gait pattern (group 2).

Limitations of our study are its retrospective nature and a relatively small number of patients in group 2. To obtain a comprehensive conclusion on the effect of multilevel interventions performed in children before the prepubertal growth acceleration, it is necessary to follow the dynamics of kinematic and kinetic data until the completion of their natural growth.

CONCLUSION

Multilevel orthopedic surgeries performed in children due to orthopedic complications before the prepubertal growth spurt are effective in improving kinematic parameters, accompanied by the development of functional abilities and increased strength characteristics of movement, only in children who did not undergo early Achilles tendon lengthening or percutaneous fibromyotomies. The results remain stable for four to five years after surgery.

Isolated Achilles tendon lengthening, or percutaneous fibrotomies, performed at an early age, hinder improvement and development of lower extremity muscles, increases in torques, and increases in muscle contraction power at long-term follow-up, even if multilevel interventions corrected bone deformities and contractures of the knee and hip joints. In the fibrotomies and early isolated Achilles tendon lengthening group, GPS parameters and gait speed worsen, and BMI increases four to five years after multilevel procedures.

Restricted hip extension with increased pelvic tilt in the sagittal plane during the support phase is a compensatory mechanism for the deficit in knee extension strength and can serve as a predictor of the development of the crouch gait pattern.

Conflict of interests None.

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Ethical approval Approval to conduct the research was obtained from the Ethics Committee of the Ilizarov National Medical Research Center of Traumatology and Orthopedics.

Informed consent Parents of the children participating in the study were present during the analysis and confirmed their informed consent for the publication of the study results without identification.

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