

Original article

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Evaluation of the condition of adolescent patients with spastic types of cerebral palsy admitted for orthopedic surgery: a cross-sectional study

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Abstract

Introduction Cerebral palsy (CP) is the most common neurological disorder in children, associated with movement disorders. The maximum age for reconstructive surgery is twelve years, but the optimal age for maintaining the results of multi-level orthopedic interventions is considered to be the second half of the adolescence period. Analysis of established orthopedic impairments and their impact on gait, as well as their characteristics depending on previous interventions, is of interest for determining the optimal conditions for reconstructive surgery on the lower extremities in adolescents.

The **purpose** of this study was to evaluate the kinematic and kinetic gait parameters of adolescents with cerebral palsy (GMFCS I–III) before orthopedic surgery using a cross-sectional comparative analysis. The null hypothesis was the absence of differences in gait parameters between patients with previous orthopedic surgery and those who did not undergo it.

Materials and methods This retrospective study included 102 adolescents aged 13–17 years with cerebral palsy, divided into two groups: Group A (GMFCS I–II, $n = 63$) and Group B (GMFCS III, $n = 39$). Three subgroups were identified in each group based on surgical history. All patients underwent computer video gait analysis. The gait analysis presents the parameters as medians with a percentile distribution level of 25 %–75 %. The unpaired Wilcoxon test ($p \leq 0.05$) was used for comparison. The relationship between the parameters was assessed using Spearman's rank correlation. The chi-square test for binary samples was used to compare the incidence of the crouch gait pattern.

Results Gait characteristics revealed a predominance of horizontal movement disorders (due to torsional deformities) in previously unoperated GMFCS I–II patients, while the prevalence of crouch gait increased in the remaining subgroups. An increase in decompensated crouch gait patterns was observed in the subgroups of patients who underwent early triceps surae interventions. A significant difference was found between groups 1A and 2A in the incidence of decompensated crouch gait (chi-square test, $p = 0.002$). No significant differences were found between the other subgroups.

Discussion The systemic nature of motor impairments in children with cerebral palsy and the resulting orthopedic disorders, necessitate not only the assessment and monitoring of individual orthopedic impairments of the lower extremity locomotor chains but also the consideration of integrated movement indices (GPS), as well as kinematic and kinetic data in their interrelationships.

Conclusion In patients with GMFCS levels I–II and no previous orthopedic interventions, indications for surgical treatment are determined by joint contractures and torsional deformities of the lower extremity segments. In patients with GMFCS level III, the crouch gait pattern, which remains compensated, predominates in adolescence. In the group of patients with triceps surae lengthening performed at an early age, the development of compensated and decompensated types of crouch gait with high-energy movements was observed. This should be taken into account both when choosing a surgical treatment strategy and during subsequent rehabilitation measures and orthotics. In adolescents with previous multilevel interventions, torsional deformities, recurrent contractures, and the development of knee flexion remained indications for surgical treatment. However, the spatiotemporal and strength characteristics of movements remained relatively high.

Keywords: spastic diplegia, cross-sectional study, crouch gait, adolescents

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INTRODUCTION

Cerebral palsy (CP) is the most common neurological disorder in children, characterized by motor impairment [1]. There is significant heterogeneity in CP manifestations, such as issues of etiology, clinical manifestations, movement and postural impairments, functional severity, and the evolution of impairments, including the development of orthopedic complications [2, 3]. This heterogeneity complicates monitoring of patient condition, particularly in terms of the evolution of impairments over a long period of time.

On average, 50–80 % of children with cerebral palsy develop walking ability [4]. However, they exhibit a wide range of deviations in both kinematic and kinetic parameters. Computerized gait analysis is recognized as a comprehensive objective test for gait assessment, allowing for the reliable monitoring of movement evolution throughout the observation period [1, 5].

A factor leading to reduction in the motor abilities of children with cerebral palsy, even to the loss of independent mobility, is the development of secondary orthopedic complications [6]. The method of multilevel surgical interventions is currently recognized and remains the most effective method for correcting these secondary orthopedic problems [7, 8].

Graham et al., summarized their clinical experience and distinguished two periods coinciding in age (4–12 years), when the place of orthopedic surgery becomes justified: the period of contractures and the period of bone deformities [9]. During these periods, the nature of orthopedic surgery is reconstructive, and palliative elements of operations (arthrodesis, reorienting osteotomies) have not yet found their indications. The publications of Shore et al. [10], Thomason et al. [11], Gough et al. [12] emphasized that the maximum age for reconstructive orthopedic interventions on the lower extremities is an age period of no older than 12 years. On the other hand, the optimal age for performing multilevel interventions is recognized as the period of the second half of pubertal growth acceleration (13–16 years), when the risk of recurrence of orthopedic problems decreases [13, 14]. Putz et al. [15] indicate a significant decrease in the effect of multilevel interventions when performed in childhood. Other authors show the stability of the positive effect of multilevel interventions, but only after a two-year interval [16]. Thus, there is a dissonance: the maximum age for reconstructive interventions is twelve years but the optimal age for maintaining the results of multilevel orthopedic interventions is the second half of adolescence.

Furthermore, there is a large cohort of patients in whom indications for surgery are identified quite late, in adolescence [17, 18]. The initial stage in determining the optimal conditions for performing reconstructive surgery on the lower extremities in adolescents is an analysis of developed orthopedic disorders and their impact on gait, as well as their characteristics based on previous interventions.

The **purpose** of this study was to evaluate the kinematic and kinetic gait parameters of adolescents with cerebral palsy (GMFCS I–III) before orthopedic surgery using a cross-sectional comparative analysis. The null hypothesis was the absence of differences in gait parameters between patients with previous orthopedic surgery and those who did not undergo it.

MATERIALS AND METHODS

This retrospective study included 102 patients with spastic cerebral palsy who underwent bilateral multilevel orthopedic intervention.

Inclusion criteria:

- Age of the second half of adolescence from 13 years until 18 years;
- Possibility to evaluate the results of computer gait analysis for levels of global motor function impairment I, II, III GMFCS;
- Interval of at least six months after a session of botulinum therapy;

- No history of selective dorsal rhizotomy;
- Interval of at least three years after the last orthopedic surgery on the lower extremities.

Exclusion criteria: more severe levels of global motor impairment; insufficient or absent instrumental gait analysis; age at the time of multilevel intervention under 13 years and older than 18 years.

According to the level of impairment of global motor functions, patients were divided into two groups: group A (GMFCS I–II, $n = 63$) and group B (GMFCS III, $n = 39$).

Within each group, based on surgical history, patients were divided into three subgroups:

- 1A and 1B — patients who did not have previous surgical interventions on the muscular system of the lower extremities;
- 2A and 2B — patients who underwent interventions on the triceps of the lower legs (lengthening of the Achilles tendon or percutaneous "minimally invasive" fibromyotendotomy) at an early age;
- 3A and 3B — patients who underwent multilevel orthopedic interventions.

In addition to the clinical and radiological examination, the patients underwent computer gait analysis, during which they walked barefoot independently or held a parent's hand on a seven-meter path at their usual walking speed. Kinematic data was recorded using 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. Analysis of kinematics and kinetics was carried out with the QTM (Qualisys) and Visual3D (C-Motion) featuring automated calculation of values. The results of a previously conducted gait analysis in a cohort of children without motor disorders were used as the norm for the corresponding age-related parameters [19].

The AtteStat 12.0.5 program (© 2002–2025 Igor Gaydyshev) was used for statistical processing. Population indicators are presented as mean values with standard deviation. The study of the hypothesis of compliance of quantitative gait parameters with a normal distribution using the Kolmogorov criterion at a significance level of ≤ 0.05 showed that the normality hypothesis is rejected. For this reason, in sample populations (identified subgroups), gait analysis indicators are presented as a median with a percentile distribution level of 25 % ÷ 75 %. 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 Spearman's rank correlation. To compare the incidence of the "crouch gait pattern", the chi-square test for binary samples was used.

The study received approval from the Ethics Board 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 provided informed consent for publication of the results and were present during the gait analysis test.

RESULTS

The distribution of demographic characteristics and gait types of patients by subgroups is presented in Table 1.

The data in Table 1 show no differences in age, gender, or body mass index (BMI) between the patient subgroups. Regarding gait characteristics, we note a predominance of horizontal movement disorders (due to torsional deformities) in previously unoperated GMFCS level I–II patients, while the proportion of crouch gait patterns increased in the remaining subgroups. An evident increase in the proportion of decompensated crouch gait patterns was observed in the subgroups of patients

following early triceps surae interventions. A significant difference was found between subgroups 1A and 2A in the incidence of decompensated crouch gait (chi-square test, $p = 0.002$). There were no significant differences in this criterion between the other subgroups.

Table 1

Patients' characteristics

Parameter	GMFCS I–II			GMFCS III		
	1A	2A	3A	1B	2B	3B
Number of patients	29	21	13	12	15	12
Age, years	14.9 ± 1.2	15.2 ± 1.3	15.4 ± 1.98	14.6 ± 1.3	14.9 ± 1.5	15.1 ± 2.4
Sex F/M	13/16	9/12	5/8	5/7	9/6	7/5
BMI	17.9 ± 3.9	19.4 ± 2.8	18.4 ± 3.22	19.3 ± 4.2	20.2 ± 3.7	19.6 ± 2.8
Type of gait						
Equinus gait with rotational disorders	4	1	3	–	–	–
Jump gait with rotational disorders	10	3	1	2	2	–
Apparent equinus	2	1	–	1	–	–
Crouch gait compensated	12	7	3	7	5	5
Crouch gait decompensated	1	4	1	2	4	1
Crouch gait+stiff knee gait	–	5	–	–	2	1
Rotational disorders, isolated	–	–	4	–	1	–
Calcaneal gait and rotational deviations	–	–	1	–	–	–
Rotational deviations and stiff knee gait	–	–	–	–	1	2
Flexed knee and rotational deviations	–	–	–	–	–	3

The comparison of the spatiotemporal characteristics of gait (Table 2) between the subgroups of patients of GMFCS level I–IIb revealed that the worst parameter values were observed in subgroup 2A (early isolated lengthening of the triceps surae): gait speed and swing period length are significantly lower, swing width and duration of the double-support phase were increased, which reflects instability of body position.

Table 2

Gait index, spatio-temporal characteristics of gait

Parameter	GMFCS I–II			GMFCS III		
	1A	2A	3A	1B	2B	3B
Gait index (GPS — gait profile score), °	12 (10.7÷15.6)	14.9 (13.68÷17.43)*	12.1 (11.4÷13.7)	20.2 (16.0÷23.9)	16.1 (15.0÷18.9)	14.5 (14.3÷15.9)* ¹
Speed, m/sec	0.93 (0.67÷1.05)	0.65 (0.53÷0.84)*	0.84 (0.66÷1.0) ¹	0.71 (0.58÷0.78)	0.65 (0.44÷0.76)	0.42 (0.38÷0.49)* ¹
Swing length, m	1.03 (0.85÷1.12)	0.84 (0.68÷0.95)*	0.95 (0.86÷1.07) ¹	0.8 (0.76÷0.91)	0.78 (0.56÷0.93)	0.74 (0.57÷0.79)
Step width, m	0.13 (0.1÷0.18)	0.17 (0.14÷0.19)*	0.17 (0.14÷0.23)* ¹	0.14 (0.135÷0.16)	0.15 (0.14÷0.18)	0.19 (0.17÷0.20)* ¹
Number of gait cycles/min	53.5 (48.4÷59)	51.5 (47.85÷55.45)	53.5 (51.65÷56.38)	51.4 (42.4÷55.6)	47.6 (41.6÷54.2)	39.8 (29.2÷46.3)* ¹
Duration of stance from the gait cycle duration, %	62.8 (61.85÷66.55)	65.7 (64.15÷72.35)*	64.1 (62.7÷67.45) ¹	64.1 (62.1÷68.9)	69.0 (66.3÷72.9)*	72.1 (68.0÷76.8)*
Duration of swing from the gait cycle duration, %	36.9 (33.13÷38.28)	33.9 (27.65÷35.48)*	35.9 (32.8÷37.6) ¹	35.4 (30.9÷38.3)	31.1 (27.4÷33.9)*	27.8 (22.4÷31.9)*
Duration of double support phase from the gait cycle duration, %	25.9 (24.85÷31.23)	32.3 (28.18÷44.98)*	29.7 (26.7÷32.8)* ¹	29.8 (26.2÷35.9)	36.7 (30.4÷46)*	39.1 (36.4÷45.2)*

Note: * — significant differences with subgroup 1A at the same GMFCS level; ¹ — significant differences between groups 2 and 3 at the same GMFCS level

The parameters in subgroup 2A (GMFCS III) reflect a regular degradation of walking parameters, correlating with the development of the crouch gait pattern: a significant increase in the movement disorder index (GPS), step width and duration of the double-support period while maintaining a relatively high walking speed.

In regard of comparing gait speed and GPS, the combination of low GPS values and comparatively slow gait speed in patients with previous multilevel interventions (subgroup 3B) is interesting. While they walk more slowly, their lower limb joint movements (amplitude and distribution) are closer to normal.

Kinematic data (Table 3) in Group 1 (GMFCS I–II) characterize the development of the crouch gait pattern predominantly in patients after isolated triceps lengthening in the early period: a continuous position of the foot in dorsiflexion, excessive flexion of the knee joint both at the moment of initial contact and in the support phase (with a maximum average flexion of 35.6° at point G1), which is accompanied by a significant decrease in the range of motion in the joint throughout the entire gait cycle compared to subgroups 1A and 3A. Also noteworthy is the decrease in the range of plantar flexion at the moment of push-off in subgroup 3A and its absence in subgroup 2A. The placement of the foot in the plantar flexion position at the initial contact and the significantly increased range of rotational movements in subgroup 1A compared to subgroups 2A and 3A indicate the predominance of the features of the jump gait and equinus gait patterns in patients who have not previously undergone surgery.

Table 3

Several kinematic parameters

Parameter	GMFCS I–II			GMFCS III		
	1A	2A	3A	1B	2B	3B
Foot position at initial contact (Γ0), °	–2.5 (–9.1÷4.4)	6.4 (1.7÷10.8)*	5.7 (0.3÷7.1)*	5.1 (–2.8÷9.75)	7.9 (2.6÷10.5)	–1.1 (–7.5÷3.1) ¹
Maximum dorsal flexion in support phase (Γ2), °	13.1 (7.3÷15.9)	17.9 (13.7÷24.4)*	15.3 (10.7÷19.6)	19 (9.9÷24.14)	24.5 (14.9÷29.8)	11.7 (8.8÷13.98) ¹
Maximum plantar flexion in propulsion (Γ3), °	–7.4 (–17.7÷–0.6)	4.8 (–0.95÷9.95)*	0.3 (–6.9÷6.5)*	–5.3 (–11.2÷7.58)	1.8 (–4.4÷9.05)*	–3.1 (–7.4÷2.95)
Foot position in swing phase (Γ4), °	5.9 (–3.5÷13.9)	14.6 (9.7÷19)*	11.8 (6.2÷14.5)	11.4 (1.98÷15.95)	13.2 (7.7÷18.4)	3.3 (–0.6÷12.3) ¹
Knee position at initial contact (K0), °	21.7 (14÷30)	33 (28.3÷40.2)*	22.2 (16.6÷26.7) ¹	46.9 (29.85÷55.3)	45.9 (29.2÷48.7)	28.7 (25.1÷35.2)* ¹
Maximum knee flexion in support phase (K1), °	28.6 (22.7÷33.2)	35.6 (31.9÷43.4)*	28.3 (19.2÷31.5) ¹	52.3 (30.8÷56.9)	47.9 (26.7÷52.0)	31.4 (29.2÷35.1)* ¹
Maximum knee extension in support phase (K2), °	9.5 (5.4÷15.4)	22.7 (14.8÷31.3)*	5.4 (1.6÷10.7) ¹	35.9 (22.8÷45.4)	33.7 (10.4÷41.7)	9.6 (1.38÷21.6)* ¹

In Group 2 (GMFCS III), excessive knee flexion at initial contact was observed in all subgroups, but was least pronounced in subgroup 3B. Sufficient plantar flexion of the foot during propulsion was present only in subgroups 1B and 3B, indicating preserved plantar flexor function, unlike in subgroup 2B. Maximum knee extension during the support phase can be considered sufficient only in subgroup 3B and reflects the effectiveness of previously performed multilevel interventions to correct sagittal plane movement disorders. However, a significant increase in pelvic and femoral rotational movements in this same subgroup indicates persistent torsional deformities of the lower extremity segments and the presence of indications for their correction. Non-operated patients and patients after early interventions on the triceps muscles of the lower legs show significant elements of the crouch gait pattern (excessive flexion in the knee joint in the support phase) or completed formation of this pattern.

Kinetic data (Table 4) show the maintenance of a sufficient level of plantar flexor strength after multilevel interventions in subgroup 3A, which does not require a compensatory increase in knee joint movement power, unlike in subgroups 1A and 2A. In groups with more severe global motor function impairments (GMFCS III), high values of generated power for gait are noted in subgroup 2B, reflecting the increased energy intensity of walking itself. Significantly low knee extension forces and sufficient extension range during the stance phase in the multilevel intervention subgroup indicate the comparatively good movements in the sagittal plane after multilevel interventions. High values of hip extension moment and generated hip movement power reflect the increased contribution of the pelvic girdle muscles to gait in all subgroups. Finally, in subgroup 2B, the need to output movement power in the knee and ankle joints again indicates increased energy intensity of walking after early isolated interventions on the triceps of the lower leg.

Table 4

Several kinetic parameters

Parameter	GMFCS I–II			GMFCS III		
	1A	2A	3A	1B	2B	3B
Hip extension torque, Nm/kg	0.9 (0.66÷1.07)	0.9 (0.76÷1.34)	0.8 (0.66÷0.98)	1.11 (0.79÷1.17)	0.94 (0.63÷1.18)	0.83 (0.49÷0.97)
Knee extension torque, Nm/kg	0.6 (0.38÷0.81)	0.7 (0.49÷0.96)*	0.7 (0.48÷0.84)	1.0 (0.61÷1.18)	0.89 (0.63÷1.15)	0.53 (0.33÷0.87)* ¹
Plantar flexion torque, Nm/kg	1.04 (0.89÷1.2)	0.99 (0.71÷1.21)	1.12 (1.03÷1.29) ¹	0.81 (0.55÷0.88)	0.9 (0.74÷0.99)*	0.87 (0.85÷0.93)*
Useful power output at the hip, W/kg	0.34 (0.06÷0.86)	0.48 (0.23÷0.86)	0.29 (0.04÷0.64)	0.47 (0.36÷0.85)	0.55 (0.4÷0.83)	0.27 (0.04÷0.57) ¹
Useful power output at the knee, W/kg	−0.45 (−0.74÷−0.09)	−0.24 (−0.69÷0.01)	−0.01 (−0.58÷0.02) ¹	−0.21 (−0.61÷0.01)	−0.34 (−0.71÷−0.03)	−0.02 (−0.23÷0.0) ¹
Useful power output at the ankle, W/kg	0.17 (−0.01÷1.12)	0.2 (−0.06÷0.42)	0.17 (0.03÷0.63)	0.15 (−0.01÷0.38)	0.29 (0.01÷0.45)	0.01 (−0.06÷0.07) ¹

Some moderate and strong correlations were found between the kinematic, spatiotemporal, and kinetic parameters in all subgroups except subgroup 1A. The negative BMI-gait speed correlation (−0.521) in subgroup 2A reflects the critical value of body mass for slowing down movement in surgical weakening of the plantar flexion function after early operations, even in patients with moderate neurological impairment. In many subgroups, plantar flexion strength had a positive significant correlation with gait speed: subgroups 2A (0.631), 1B (0.738), 2B (0.797), 3B (0.673). Moreover, walking speed decreases with increasing ankle joint range of motion, as a consequence of the development of pathological excessive dorsiflexion of the foot in patients with GMFCS level III. The correlation becomes negative for subgroups 1B (−0.761) and 3B (−0.689). The importance of plantar flexion strength is also shown by the negative correlation of this parameter with GPS (−0.522) in subgroup 3A. The positive correlation between knee extension range of motion (K1–K2) during the stance phase and the efficiency of generated power during knee joint movements in subgroup 2A reflects sufficient compensatory potential even with early weakening of the plantar flexors.

However, at a more severe level of global motor function impairment (GMFCS III), a significant positive correlation is observed between GPS and kinematic or kinetic parameters in subgroup 3B. This reflects the development of functional decompensation due to orthopedic impairments: with the hip extension power (0.522), with the knee extension power (0.533), with the total power of movements in the knee (0.739) and ankle (0.565) joints. Moreover, for this subgroup, a positive correlation was found between BMI and the knee extension power (0.630) and plantar flexion of the foot (0.649). thus, a positive correlation was found between BMI values and the total generated power of movements in the ankle joint (0.543), which reflects the preservation of the adaptive capacity of plantar flexors in patients

after multilevel interventions. Finally, we note the importance of the identified significant negative correlation "GPS-range of motion in the sagittal plane in the hip joint" (-0.619) in subgroup 1B, probably reflecting the capability of compensating for the decrease in the motor abilities of the knee and ankle joints by increasing the motor activity of the pelvic girdle muscles.

DISCUSSION

A critical element in the pathogenesis of motor disorders and secondary orthopedic complications is the progressive reduction in the range of passive movements during child's growth [20]. The development of muscle length deficit, initially caused by spasticity, evolves towards retraction [21]. The morphological changes observed in muscles are accompanied by an increase in sarcomere length, a decrease in the number of satellite cells, and an increase in collagen structures, which causes a decrease in contractile force, a decrease in regenerative potential, and an increase in muscle stiffness observed due to other orthopedic complications of cerebral palsy [22, 23].

In clinical practice, multilevel interventions are usually performed at the age of 11–15 years; they are accompanied by the stability of the surgical result without regression, especially if the intervention is performed after the pubertal growth acceleration [24, 25]. At the age of over 12 years, full anatomical restoration of the structures and relationships between the limb segments and muscle proportions is often no longer possible, and the only solution is palliative orthopedic surgery for crouch gait [9, 26]. This is why Graham et al. [9] distinguish the age period of 4–12 years (the period of contractures and bone deformities), when orthopedic surgery becomes justified. During this period, the nature of orthopedic surgery is reconstructive, and palliative interventions do not have indications yet.

Adolescence, after the peak of growth acceleration in the lower extremities has passed, still belongs to the period of childhood and is termed as senior school age [27, 28]. At this age, there is still a large cohort of patients with indications for surgical correction of cerebral palsy complications [17, 18]. A specific feature of operations and their result prognosis is the lack of remodeling potential in the process of residual growth and the onset of early arthrotic changes [9, 15]. That is why in adolescence, when the pubertal growth acceleration slows down and the child's BMI gradually increases, surgical treatment is often aimed at correcting the crouch gait pattern [9]. Moreover, the results of correction, due to the cessation of active longitudinal growth of the long bones of the lower extremities, remain relatively stable in the late period [7, 15].

Various factors may explain the relatively late orthopedic interventions, often of a palliative nature. A number of authors attribute this situation to drawbacks of healthcare system organization. The lack of a consistent and comprehensive approach to treating children with cerebral palsy is low availability of medical care, inadequate awareness among physicians of evidence-based treatment methods, late diagnosis of the disease, and inadequate parental awareness of the nature of the disease and the effectiveness of various treatment methods, as well as the lack of national registries [29, 30, 31].

An unfavorable factor that combines age and surgical aspects is the performance of so-called fibromyotomies, fibrotomies, and Achilles tendon lengthening at an early age. Groundless orthopedic interventions on spastic muscles, even the ones that increase passive range of motion in the joints, lead to their excessive weakening, which manifests itself in early functional decompensation and the development of iatrogenic disorders and orthopedic complications in adolescence, resulting in the formation of the iatrogenic crouch gait pattern [5, 32, 33].

It should be noted that there is a certain group of patients in whom the correction of orthopedic complications of cerebral palsy was not fully achieved even with multi-level interventions; in particular, correction of torsion deformities was not performed [34, 35, 36]. In some cases,

recurrence of contractures is possible, which may also require repeated interventions, the frequency of which (excluding the removal of osteosynthesis material) in the late period after primary multilevel operations reaches 39 %. Thus, Terjesen et al. [25] indicate the development of mild foot equinus after three to four years of follow-up with normal kinematic parameters in the support phase, which is accompanied by a progressive decrease in the range of dorsiflexion during subsequent growth at an average rate of 4° per year. Finally, planning the volume of multilevel interventions without the use of computer gait analysis increases the risk of inadequacy, insufficiency or inaccuracy in the amount of surgical correction, which requires repeat interventions in the future [37, 38].

In our study, gait parameters varied significantly between the subgroups. In patients with mild global motor impairment (GMFCS I-II) and no previous orthopedic interventions, rotational movement disorders and contractures of the knee and ankle joints remained the dominant gait disorders. However, kinetic movement characteristics remained relatively intact. Therefore, surgical interventions indicated in this situation are strictly reconstructive in nature, as there is no decompensation of movements in the sagittal plane. In the group of patients with similarly mild motor impairments (GMFCS I-II), but who had undergone isolated triceps lengthening surgery at an early age, decompensation of motor impairments with the development of an iatrogenic crouch gait pattern was observed in most cases. This pattern was accompanied by both deterioration in the spatiotemporal characteristics of gait and an increase in its energy consumption. In the subgroup of multilevel interventions in GMFCS I–II patients, indications for surgical treatment were due to individual unresolved orthopedic problems, such as rotation or recurrent contractures.

We believe that in the GMFCS III subgroup without previous surgical interventions, movement disorders naturally reflected the final stage of the typical crouch gait pattern, characterized by a full deterioration in spatiotemporal parameters and an increase in movement energy consumption, but with a predominance of compensated forms. In the subgroup of adolescents with global movement disorders of the same level (GMFCS III), but after isolated interventions on the triceps surae, decompensated forms of crouch gait predominated. In the subgroup after previous multilevel interventions, GMFCS III patients demonstrated impairments characterized by rotational deviations, knee flexion without excessive dorsiflexion of the foot, and a compensated crouch gait pattern. However, the adaptive capacity of the plantar flexors is preserved in the patients after multilevel interventions, and the integral GPS index has the lowest values for GMFCS III level patients.

Overall, it can be noted that the best values for spatiotemporal gait parameters and the absence of crouch gait are observed in the patients who maintain sufficient plantar flexion strength and lack excessive dorsiflexion of the foot during the stance phase. This is confirmed by the significant negative correlation in subgroup 2B between BMI and gait speed, as well as the negative correlation between the total range of motion in the ankle joint and gait speed.

It is known that there is a natural evolution of movement disorders towards the crouch gait pattern that develops in adolescence in patients with spastic diplegia, caused, among other things, by torsion deformities of the femurs, foot deformities and high position of the patella [9, 25, 35, 39]. However, a predictor of this unfavorable evolution, clearly shown in the studies of Pilloni et al. [32], is surgical weakening of the plantar flexors, which leads to an increase in the minimum flexion of the knee joint in the stance phase. The study of Bernthal et al. [40] noted that decompensation of the extension function of the lower limb initially manifested itself as a tendency to excessive dorsiflexion of the foot in the stance phase. In our study, the obvious adverse walking parameters in adolescents with a history of isolated triceps lengthening confirms the negative effect of percutaneous fibromyotomies and Achilles tendon lengthening, which manifests itself in late childhood and adolescence.

The limitations of our study include the cross-sectional nature of the study and the lack of a retrospective analysis of kinematic and kinetic gait parameters in this group of patients. Another limitation is the relatively small number of patients in the compared groups. A significant limitation is the comparison of groups divided by the level of global motor impairment, but without an in-depth neurological analysis. Furthermore, the study did not include patients who had previously undergone multilevel interventions but who did not have indications for repeat surgery in the long-term period. To obtain a comprehensive conclusion on the motor status of the studied patient groups, we plan to compare data with gait parameters using the FMS scale in future studies and assess patients' quality of life, which will provide a more complete picture of the condition of adolescent cerebral palsy patients admitted for orthopedic surgery. Finally, we note that the purpose of the study was not to compare patient groups, but to identify characteristic features of motor impairments that allow us to describe and individualize categories of gait disorders in adolescent patients admitted for surgery.

CONCLUSION

In patients with spastic diplegia admitted for surgery in adolescence, indications for orthopedic intervention are determined by the level of global motor impairment, as well as by the type and extent of previous surgeries. In patients with GMFCS levels I–II who have no previous surgeries, indications are determined by the presence of joint contractures and torsion deformities of the lower extremity segments. In contrast, in patients with GMFCS level III, a compensated crouch gait pattern predominates in adolescence. We observed the development of compensated and decompensated forms of crouch gait with high energy consumption movements in a group of patients who underwent triceps surae lengthening at an early age. This should be considered when choosing a surgical approach, subsequent rehabilitation measures, and fitting orthotics. After multilevel interventions performed in the earlier period, indications for surgical treatment in adolescents remained torsion deformities, recurrent contractures, and the development of flexion position of the knee joint; however, the spatio-temporal and strength characteristics of movements remained at a relatively high level.

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