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Kinematic analysis of gait in children with rigid flatfoot before and after surgical treatment

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Abstract

Aim – to study the kinematics and kinetics of walking in children with rigid flatfoot by comparing data before and after surgical operations.

Material and methods. The study included 51 patients (42 boys, 9 girls) with rigid flatfoot, with a mean age of 10.5 ± 1.4 years. They were stratified by disease stage and underwent surgical treatment using the author's technique: 'transposition of the m. peroneus longus tendon medially, shortening of the m. tibialis posterior tendon, and arthrodesis of the cuneo-navicular joint'.

Results. It was found that higher disease stages correlated with increased step time and support time, and decreased swing time, average walking speed, and step frequency (<0.01 to <0.001). Disease progression also exacerbated pathomorphological changes in the foot, driven by biomechanical dysfunction

of the lower leg's pronator and supinator muscles, alongside reduced gait energy efficiency.

Conclusion. Gait kinematic assessment, when combined with standard diagnostic tools for rigid flatfoot (e.g., radiography and podometry), enhances the identification of effective and precise treatment strategies. The proposed disease stage-adjusted corrective approach addresses all components of rigid flatfoot: it eliminates pathological pronation, restores supination and plantar flexion function, and achieves adequate foot arch reconstruction.

Keywords: flatfoot, muscle rigidity, kinematics, children.

Conflict of interest: nothing to disclose.

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Исследование кинематики ходьбы детей с ригидным плоскостопием до и после хирургического лечения

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Аннотация

Цель – изучить кинематику и кинетику ходьбы у детей с ригидным плоскостопием путем сравнения данных до и после проведенных хирургических операций.

Материал и методы. В исследование включен 51 пациент (42 мальчика и 9 девочек) с ригидным плоскостопием. Средний возраст пациентов со-

ставлял $10,5 \pm 1,4$ года. Пациенты разделены на группы с учетом стадии заболевания. Всем пациентам проведено хирургическое лечение с применением авторской методики – «транспозиция сухожилия m. peroneus longus в медиальную сторону стопы, укорочение сухожилия m. tibialis posterior и артродезирование клинолабевидного сустава».

Результаты. Определено, что чем выше стадия заболевания, тем более увеличены показатели «время шага», «время опоры» и уменьшены показатели «время переноса», «средняя скорость ходьбы» и «частота шагов» ($<0,01-0,001$). Также от стадии заболевания зависят степень патоморфологических изменений в области стопы на фоне нарушения биомеханической особенности мышц-пронаторов и мышц-супинаторов области голени и потеря высокой энергии при ходьбе.

Заключение. Оценка кинематики ходьбы в дополнение к таким методам диагностики ригидного плоскостопия, как рентгенография и по-

дометрия, полезна для определения эффективных и точных методов лечения заболевания. Предложенный метод коррекции с учетом стадии заболевания позволяет устранить все компоненты ригидной формы плоскостопия, ликвидировать патологическую пронацию, улучшить функцию супинации и подошвенного сгибания с адекватным восстановлением свода стопы.

Ключевые слова: плоскостопие, мышечная ригидность, кинематика, дети.

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INTRODUCTION

Rigid flatfoot represents the most prevalent form of foot dysfunction [1]. It is characterized by a lowered longitudinal foot arch, but in fact represents a three-dimensional deformity comprising hind-foot valgus, forefoot abduction, and pronation due to the severity of foot pathology [2, 3]. Rigid flatfoot disrupts the normal gait pattern and establishes a new pathological walking type. Analysis of these abnormal movement patterns enables diagnosis of disease etiology and pathogenesis, while identifying individual and clinical variants [4, 5].

The treatment of rigid flatfoot differs significantly from the mobile form of this pathology and often requires invasive surgical interventions [6]. Surgical correction of rigid flatfoot varies in technique and scope, from soft tissue procedures involving talar bone reshaping with tendon/muscle transfers to osseous methods utilizing various metal fixation devices [7]. However, long-term postoperative outcomes remain unpredictable and often prove unsatisfactory for patients, their parents and orthopedic surgeons, particularly due to the need for permanent orthotic use to manage clinical symptoms [8]. This stems from insufficient data on pathogenetic features of rigid flatfoot, biomechanical impairment of lower leg/foot neuromuscular structures across disease stages and severity levels, and the disregard of these factors when selecting corrective procedures for rigid flatfoot patients [9].

A current priority is investigation of rigid flatfoot kinetics and kinematics using advanced methods such as gait videography and 3D motion capture in gait laboratories.

AIM

To study the kinematics and kinetics of walking in children with rigid flatfoot by comparing data before and after surgical operations.

MATERIAL AND METHODS

The study group included 51 patients (42 boys and 9 girls) with rigid flatfoot, who were observed and treated in the Andizhan Children's Multi-disciplinary Clinic in 2019–2024. The mean age of patients was 10.5 years (from 7 to 16).

Based on the classification of M.S. Myerson (1997), we developed a new algorithm for classification of children with rigid flatfoot¹. Unlike the Myerson classification, we included the spastic contracture of the tendon of m. peroneus longus, which has a special role in the pathomorphological changes of the lower leg and foot in rigid flatfoot (Table 1).

It is seen from Table 1 that among clinical forms the acquired form was most prevalent, in 41 (80.5%) vs. 10 (19.5%) cases of congenital form of the disease. Most frequently, patients were registered with stage III, in 22 (43.1%) cases, and there were also cases with spastic contracture of the tendon of m. peroneus longus, in 13 (25.5%) cases (subgroup III B) among patients with stage III, and in 8 (15.7%) cases (subgroup IV B) among patients with stage IV of the disease.

The functional condition of the m. peroneus longus is principal in the transformation of the mobile flatfoot into rigid flatfoot. Tendon reposition to the supinator side is also critical for surgical correction.

All patients (n=51) underwent surgical treatment using following technique: 'transposition of the m. peroneus longus tendon medially, shortening of the m. tibialis posterior tendon, and arthrodesis of the cuneo-navicular joint'².

The technique involves the following steps: wedge resection of the navicular and cuneiform articular surfaces (wedge angle oriented plantarly), creating a cuneiform bone tunnel; reinserting the m. tibialis posterior tendon attachment, shortening its tendon via tensioning and embedding into the formed tunnel of the cuneiform bone; transferring the m. peroneus longus tendon medially to attach to the m. tibialis posterior tendon; and triangular pin fixation of the cuneo-navicular joint to reconstruct the foot arch.

It is to be remembered that in rigid flatfoot, even after its restoration, the patients' gait will vary. To distinguish between these variations of gait, we analyzed it in the gait laboratory. Our study considered the severity of the disease, age of patients and their anthropometric data. The study involved 13 patients with stage II of disease, 22 patients with stage III, and 16 patients with stage IV. The mean height of patients was 126.5 cm (126-162 cm) for boys and 138.6 cm (133-146 cm) for

¹ The Algorithm is registered in the Agency for Intellectual Property of the Republic of Uzbekistan (No. DGU42326, 2024).

² Invention patent No.FAP 2416 (2024), registered in the Agency for Intellectual Property of the Republic of Uzbekistan.

Disease stage	I	II (n=13)	III (n=22)		IV (n=16)	
Clinical forms				III B (n=13)	IV A (n=8)	IV B (n=8)
Congenital, n=10 (19.5%)	0	2 (3.9%)	2 (3.9%)	2 (3.9%)	3 (5.9%)	1 (1.9%)
Acquired, n=41 (80.5%)	0	11 (21.6%)	7 (13.7%)	11 (21.6%)	5 (9.9%)	7 (13.7%)

Table 1. Distribution of patients by clinical form and stage of rigid flatfoot

Таблица 1. Распределение больных по клинической форме и стадии ригидного плоскостопия

girls. The mean weight of patients was 32.5 ± 2.4 kg (21-62 kg) among boys, and 28.2 ± 3.1 kg (26-41 kg) among girls, respectively.

Gait analysis was performed using video recording and 3D motion capture at the Gait Laboratory of the Republican Specialized Scientific-Practical Medical Center of Traumatology and Orthopedics.

Range of motion for each joint was measured using a goniometer, including ankle plantarflexion and dorsiflexion. During dorsiflexion measurement, the foot was slightly everted to stabilize the subtalar joint and prevent compensatory motion.

For 3D motion capture, passive reflective markers were placed according to the Helen Hayes protocol. Marker trajectories were recorded using the BTS Bioengineering system (Italy, 2023) with eight digital infrared cameras.

The participants' gait was recorded during multiple trials on a 12-meter walkway at self-selected speed, with motion capture at 120 frames per second (120 Hz).

Ground reaction force (GRF) was measured using four force plates embedded in the midpoint of the walkway. GRF between the limb and surface during stance phase was quantified by the force platforms.

The coordinate system of Euler angles for measuring GRF was placed as shown in **Fig. 1**.

RESULTS

In the gait laboratory, we tested such parameters as step time (sec), stance time (sec), swing time (sec), stance phase (%), swing phase (%), single-limb support phase (%), double-limb support phase (%), average velocity (m/s), and cadence (steps/

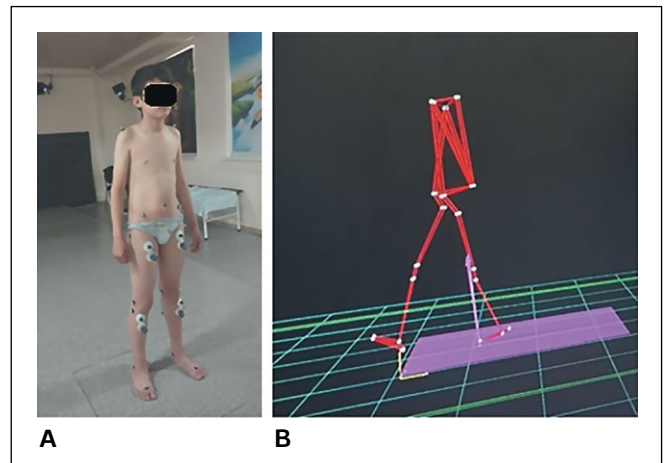


Figure 1. A – appearance of the patient under study; B – coordinate system of Euler angles for measuring GRF.

Рисунок 1. А – внешний вид исследуемого пациента; Б – система координат углов Эйлера для измерения GRF.

min). The obtained results were compared with normative values. Step time, the key gait parameter, was calculated as the sum of 'stance time' and 'swing time'.

The analysis of data of 13 patients with stage II of the disease showed that the step time of both lower limbs were 43% above normative values ($p=0.001$). The values of such parameters as stance time and swing time were 52% and 31% higher than the normative values, respectively. Statistical significance was found between the results ($p=0.001$).

Analysis of pre-operative gait data (videography and 3D motion capture) in stage II rigid flatfoot revealed minimal

Parameter	Right lower limb	Left lower limb	Normative values	p-value
Step time (s)	1.33 ± 0.07	1.33 ± 0.04	0.93 ± 0.04	<0.001
	0.98 ± 0.05	0.97 ± 0.04		
Stance time (s)	0.82 ± 0.04	0.80 ± 0.03	0.54 ± 0.05	<0.001
	0.60 ± 0.02	0.56 ± 0.05		
Swing time (s)	0.51 ± 0.03	0.53 ± 0.01	0.39 ± 0.03	0.01
	0.38 ± 0.02	0.41 ± 0.02		
Stance phase (%)	61.2 ± 2.88	61.2 ± 3.4	57.97 ± 1.93	<0.05
	60.2 ± 2.1	60.1 ± 1.4		
Swing phase (%)	38.6 ± 2.4	38.8 ± 2.1	42.03 ± 1.93	<0.001
	40.5 ± 2.6	41.8 ± 2.5		
Single-limb support phase (%)	37.3 ± 2.9	40.5 ± 1.4	39.28 ± 0.25	<0.05
	38.3 ± 2.9	40.1 ± 1.1		
Double-limb support phase (%)	10.75 ± 2.4	8.5 ± 2.3	12.4 ± 2.21	>0.05
	11.5 ± 2.2	11.9 ± 2.1		
Average velocity (m/s)	0.86 ± 0.1		1,2 ± 0,2	1.2 ± 0.2
	1.16 ± 0.3			
Cadence (steps/min)	86.3 ± 5.6		129,6 ± 8,4	129.6 ± 8.4
	125.5 ± 4.5			

Table 2. Comparative analysis of results of 13 patients with stage II of the disease before and after surgery

Таблица 2. Сравнительный анализ результатов 13 больных со II стадией заболевания до и после операции

Parameter	Right lower limb	Left lower limb	Normative values	p-value
Step time (s)	1.39 ± 0.07	1.40 ± 0.04	0.93 ± 0.04	<0.001
	1.15 ± 0.05	1.16 ± 0.03		
Stance time (s)	0.83 ± 0.04	0.87 ± 0.02	0.54 ± 0.05	0.01
	0.61 ± 0.03	0.60 ± 0.02		
Swing time (s)	0.56 ± 0.03	0.53 ± 0.02	0.39 ± 0.03	0.01
	0.54 ± 0.02	0.56 ± 0.01		
Stance phase (%)	61.6 ± 3.6	61.8 ± 2.8	57.97 ± 1.93	0.01
	59.6 ± 4.4	59.8 ± 1.8		
Swing phase (%)	38.4 ± 1.9	38.2 ± 2.2	42.03 ± 1.93	<0.001
	39.1 ± 2.9	40.3 ± 3.1		
Single-limb support phase (%)	37.4 ± 2.7	40.9 ± 1.7	39.28 ± 0.25	0.01
	38.6 ± 3.5	39.9 ± 1.1		
Double-limb support phase (%)	10.75 ± 2.4	9.7 ± 2.6	12.4 ± 2.21	<0.05
	11.6 ± 1.6	11.8 ± 1.04		
Average velocity (m/s)	0.79 ± 0.1		1,2 ± 0,2	1.2 ± 0.2
	1.12 ± 0.2			
Cadence (steps/min)	82.7 ± 5.2		129,6 ± 8,4	129.6 ± 8.4
	124.9 ± 3.1			

Table 3. Comparative analysis of results of 22 patients with stage of the disease before and after the surgery

Таблица 3. Сравнительный анализ результатов 22 больных с III стадией заболевания до и после операции

energy loss during walking, attributable to the following: absence of rigid contracture or spasm of the m. peroneus longus tendon, and preserved foot arch mobility with minimal degenerative changes in tarsometatarsal joints. Fibrous coalition between metatarsals was also diagnosed in patients with stage II of the disease.

The preoperative values of such parameters as step time, stance time, and swing time significantly influenced the average velocity and cadence, which were below the norm. The average velocity was 0.86 ± 0.1 m/s (norm: 1.2 ± 0.2 m/s), cadence, 86.3 ± 5.6 steps per minute (norm: 129.6 ± 8.4). The obtained results demonstrated statistical significance ($p=0.001$) (**Table 2**).

The surgical interventions created optimal conditions for improving foot spring function with minimal energy loss during gait, eliminating the need for metatarsal coalition resection. Postoperative correction in stage II patients demonstrated statistically significant improvements: step time

bilaterally reached 0.93 ± 0.05 sec ($p<0.01-0.001$), stance time 0.60 ± 0.02 sec (all $p=0.001$), and swing time 0.38 ± 0.02 sec ($p=0.001$). The enhancements of parameters of step increased average walking velocity from 0.86 ± 0.1 m/s to 1.16 ± 0.3 m/s (normal range: 1.2 ± 0.2 ; $p=0.001$) and cadence from 86.3 ± 5.6 to 125.5 ± 4.5 steps/min (norm: 129.6 ± 8.4 ; $p=0.001$).

In 22 patients in stage III of the disease, the step time, stance time and swing time parameters were significantly above the norm, by 49%, 54% and 43% respectively ($p=0.001$). The parameters of the step significantly influenced the average velocity and cadence. The average velocity in the preoperative period was 0.79 ± 0.1 m/s, which is significantly lower than the normative value of 1.2 ± 0.2 m/s. The cadence was 82.7 ± 5.2 steps per minute, also significantly below the norm of 129.6 ± 8.4 . The results demonstrated statistical significance ($p=0.001$) (**Table 3**).

In stage III rigid flatfoot, prolonged arch collapse and the rigid spasm of the m. peroneus longus tendon induce severe

Parameter	Right lower limb	Left lower limb	Normative values	p-value
Step time (s)	1.43 ± 0.04	1.44 ± 0.05	0.93 ± 0.04	<0.001
	1.18 ± 0.06	1.19 ± 0.06		
Stance time (s)	0.86 ± 0.02	0.86 ± 0.03	0.54 ± 0.05	<0.001
	0.63 ± 0.02	0.62 ± 0.03		
Swing time (s)	0.57 ± 0.02	0.58 ± 0.02	0.39 ± 0.03	<0.001
	0.55 ± 0.04	0.57 ± 0.03		
Stance phase (%)	63.1 ± 4.6	63.5 ± 4.6	57.97 ± 1.93	<0.05
	60.8 ± 4.5	60.9 ± 4.6		
Swing phase (%)	35.9 ± 5.3	35.2 ± 5.1	42.03 ± 1.93	<0.001
	38.2 ± 2.3	38.8 ± 6.1		
Single-limb support phase (%)	35.6 ± 4.7	38.6 ± 4.9	39.28 ± 0.25	<0.05
	38.4 ± 2.2	38.9 ± 0.35		
Double-limb support phase (%)	8.72 ± 2.9	8.6 ± 2.7	12.4 ± 2.21	<0.05
	10.79 ± 3.9	10.89 ± 1.85		
Average velocity (m/s)	0.73 ± 0.30		1,2 ± 0,2	1.2 ± 0.2
	1.05 ± 0.05			
Cadence (steps/min)	76.2 ± 9.1		129,6 ± 8,4	129.6 ± 8.4
	115.2 ± 7.4			

Table 4. Comparative analysis of results of 16 patients with stage IV of disease before and after the surgery

Таблица 4. Сравнительный анализ результатов 16 больных с IV стадией заболевания до и после операции

degenerative changes, producing fibrous or cartilaginous tarsometatarsal coalitions. Concomitant dysfunction of the m. tibialis posterior tendon further compromises the spring function of the foot, resulting in excessive energy expenditure during gait.

In stage III of the disease, priority is given to coalition resection that yields limited intermetatarsal joint mobility. This step is followed by the transfer of the m. peroneus longus tendon to the supinator side and shortening of the m. tibialis posterior tendon. This converts rigid flatfoot to a mobile form, significantly improving muscle function supporting lower leg and foot spring mechanics while minimizing gait energy loss. Postoperative outcomes demonstrated near-normal improvement of parameters ($p=0.001$).

In 16 patients with stage IV of the disease, the values of step time, stance time and swing time were significantly increased versus the norm by 54%, 59% and 46% respectively ($p<0.001$). The values of average velocity and cadence were also significantly lower: in the preoperative period, the average velocity was 0.73 ± 0.03 m/s, statistically significantly lower than the norm of 1.2 ± 0.2 m/s, and the cadence was decreased to 76.2 ± 9.1 steps per minute versus the normative value of 129.6 ± 8.4 steps per minute ($p=0.001$) (Table 4).

Stage IV patients exhibit bony or cartilaginous tarsometatarsal coalitions with severe rigid spasm of the m. peroneus longus tendon, indicating profound arch spring dysfunction and talocalcaneal osteoarthritis. The energy-absorbing capacity of the foot is markedly impaired, resulting in excessive energy loss even during short-distance walking.

We first resected the bony or cartilaginous coalition, then performed medial transfer of the m. peroneus longus tendon with shortening of the m. tibialis posterior tendon, thus achieving essential mobilization of the foot arch.

Postoperative supinator muscle function and foot spring mechanics were adequately restored, though ankle pain persisted due to tarsometatarsal osteoarthritis. Postoperative values of the step time, stance time and swing time parameters significantly decreased to 1.18 ± 0.06 from 1.43 ± 0.04 sec, to 0.63 ± 0.02 from 0.86 ± 0.02 sec, and to 0.55 ± 0.04 from 0.57 ± 0.02 sec, respectively ($p<0.001$). The average velocity increased in the postoperative period to 1.05 ± 0.05 m/s (norm: 1.2 ± 0.2 m/s). The cadence value also increased to 115.2 ± 7.4 steps per minute, which is significantly closer to the norm (129.6 ± 8.4

steps per minute). The obtained results demonstrated statistical significance ($p<0.001$).

DISCUSSION

Rigid flatfoot is characterized with lever arm shortening due to forefoot abduction and heel valgus, reducing lever strength and mid-foot flexibility, respectively [10]. This impairs kinetic lever function, causing loss of kinetic energy. From the standpoint of clinical symptoms, this manifests as muscle fatigue after prolonged walking, discomfort or pain in the foot, leg, or knee [11,12].

Studies revealed comparable reductions in both plantarflexion and dorsiflexion range of motion at the ankle joint in these patients. Flatfoot was associated with an increased angle between the talar and navicular bones. Consequently, greater energy expenditure was required for supination and inversion to achieve foot stabilization during gait [13,14].

Podiatric practice recognizes over 100 surgical techniques for the correction of the planovalgus deformity, yet no optimal treatment protocol exists. Pediatric surgical interventions are categorized as follows: soft-tissue procedures, extra-articular bony operations, and intra-articular surgeries [15,16]. Combined approaches yield superior outcomes in most cases [17,18].

At the same time, the incidence rate of various complications and relapses is rather high reaching 23.7%. Given the multicomponent nature of the morphological changes of the foot joint and the multifactorial etiology of the flatfoot, each case requires individual indications and corrective method selection [19–22].

CONCLUSIONS

1. Gait kinematic analysis complements standard rigid flatfoot diagnostics (radiography, podometry) to optimize treatment precision.

2. The analysis included measurements of the degree of kinetic energy loss in the gait of flatfoot patients and identified a biomechanical correlation between the degree of energy loss and the stage of rigid flatfoot.

3. The suggested method of correction, taking into account the disease stage, allows immediate elimination of all components of the rigid form of flat foot, eliminate pathological pronation, improve supination and plantar flexion of the foot, and adequate restoration of the foot arch. ■

ADDITIONAL INFORMATION	ДОПОЛНИТЕЛЬНАЯ ИНФОРМАЦИЯ
Ethical review. All patients (their legal representatives) gave informed consent to participate in the study.	Этическая экспертиза. Все пациенты (их законные представители) дали информированное согласие на участие в исследовании.
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Conflict of Interest. The authors declare that there are no obvious or potential conflicts of interest associated with the content of this article.	Конфликт интересов. Авторы декларируют отсутствие явных и потенциальных конфликтов интересов, связанных с содержанием настоящей статьи.
Contribution of individual authors. I.Yu. Khodjanov: idea of the research, editing of the article. X.I. Umarov: writing of the text. Sh.K. Khakimov: statistical data processing, literature review. A.G. Mirzaev: performing gait in lab analysis and data processing. The authors gave their final approval of the manuscript for submission, and agreed to be accountable for all aspects of the work, implying proper study and resolution of issues related to the accuracy or integrity of any part of the work	Участие авторов. И.Ю. Ходжанов – идея исследования, редактирование статьи. Х.И. Умаров – написание текста. Ш.К. Хакимов – статистическая обработка данных, обзор литературы. Мирзаев А.Г. – проведение анализа в лаборатории походки и обработка данных. Все авторы одобрили финальную версию статьи перед публикацией, выразили согласие нести ответственность за все аспекты работы, подразумевающую надлежащее изучение и решение вопросов, связанных с точностью или добросовестностью любой части работы.

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