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**Original article**

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# *Quantitative parameters of the kinetics and kinematics of the iatrogenic crouch gait pattern*

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***Abstract***

The pattern of pathological crouch gait in patients with spastic paralysis is characteristic of diplegic forms and in natural development manifests itself usually after the age of 10-12 years. This pathological gait may develop earlier after early surgical interventions that weaken the triceps of the lower leg, especially the soleus muscle. The heterogeneity of the crouch gait pattern is diverse. Qualitative assessment of the difference in the decompensated crouch pattern, especially associated with stiff-knee gait, according to the graphs of kinematics and kinetics of the joints can be difficult, and quantitative criteria for differentiation have not been reflected in the literature. The **purpose** of the study was to conduct a comparative analysis of the quantitative parameters of the compensated, decompensated and associated stiff-knee gait crouch pattern. **Materials and methods** The assessment of the locomotor profile by 3D gait analysis (3DGA) was carried out in stationary conditions in 27 children (54 limbs) with spastic diplegia, who had previously undergone percutaneous fibromyotomy according to the Ulzibat method, or open lengthening of the Achilles tendon. The mean age at the time of the survey was 13.0 (8–17) years. Control group: 19 children without orthopedic pathology (38 limbs) of the same age. Three groups of changes within the crouch gait pattern, recorded on separate limbs, were distinguished: I – model of the crouch pattern of the “compensated” type (n = 30); II – model of the crouch pattern of the "decompensated" type (n = 14); III – models of crouch pattern of the "stiff-knee" type (n = 10). **Results** An analysis of the evaluation of the models of compensated, decompensated, and stiff-knee patterns of crouch gait revealed criteria for their differentiation in terms of quantitative indicators of kinematics and kinetics. GPS: compensated and decompensated crouch gait up to 25.0, stiff-knee gait – more than 25.0. The angle of maximum dorsiflexion of the foot in the stance phase: compensated and decompensated crouch pattern up to 35.0°, stiff-knee crouch pattern – more than 35.0°. Knee joint extension range: compensated crouch over 11.0°, stiff-knee gait up to 6.0°. Flexion knee joint range: compensated crouch more than 11.0°, stiff-knee gait – up to 6.0°. The strength of the leg extensor muscles during the formation of the support push: compensated and decompensated crouch less than 1.0 H*m/kg, stiff-knee – more than 1.0 N*m/kg. The strength of the leg flexor muscles in the midstance period: compensated crouch less than 0.25 H*m/kg, stiff-knee – more than 0.75 N*m/kg. Absorption power (negative) of the knee joint: compensated and decompensated crouch more than 0.9 W/kg, stiff-knee less than -0.9 W/kg. Useful peak power of the joints: compensated and decompensated crouch patterns – more than 0.40 W/kg, stiff-knee gait – less than 0.40 W/kg. **Conclusions** The development of the crouch gait pattern in the absence of a tertiary compensatory deviation (torso tilt) can be formed with or without a decrease in the power of the joints. The decompensated and compensated types of the crouch pattern have a significant difference in the kinematics of the knee joint and in the duration of the internal moment of extension, while the power parameters of the joints do not have significant differences. Stiff-knee associated crouch pattern is the most severe type in which all the power parameters of the joints are decreased. The manifestation of the severity of this pathological pattern may vary between the right and left limbs of the individual.
**Keywords**: 3D computerized gait analysis, iatrogenic crouch, compensated crouch, decompensated crouch, stiff-knee

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The combination of quantitative parameters of gait and its classification according to multi-joint (MJ) patterns is of key importance for a comprehensive definition of gait pathology in children with cerebral palsy (CP). Crouch gait is a common pathological walking pattern in cerebral palsy, which is characterized by excessive flexion of the hip, knee, and permanent dorsiflexion of the feet, what is accompanied by increased energy consumption of the child for walking [1].

The most common cause of the crouch gait in children with spastic diplegia is the weakness of the plantar flexion of the ankle joint by 40–60 % relatively to their healthy peers of the corresponding age, which is necessarily combined with the pathology of the levers in the horizontal plane (torsion deformities and/or pathological deviation of the foot axis outward), which leads to a displacement of the support reaction vector posteriorly from the knee joint at any moment of the support phase of the gait [2-4].

In addition to the natural development of this gait pattern, there is an iatrogenic crouch gait pattern which is formed after unjustified fibromyotomies and isolated lengthening of the Achilles tendon performed at an early age. Moreover, an asymmetry in the severity of this type of movement disorders may develop between the limbs even in one person [5-9]. The subsequent inevitable weakening of the triceps of the lower leg leads to a loss of function of the soleus muscle and pathological (initially adaptive) flexion of the knee joint in the support phase. The age of indications for orthopedic surgical treatment is significantly lower in the group of iatrogenic gait disorders, than in the group with naturally developed gait pathology [10, 11].

The "golden" standard for gait assessment is three-dimensional computerized gait analysis (3DGA), which provides accurate and reliable information about the child's gait pattern and provides its objective documentation [12-14]. A combination of kinetic and kinematic parameters of the general gait model is recommended as an expert level for objective documentation of detectable changes [15, 16].

According to the results of 3D gait analysis, the crouch gait pattern can be subdivided into compensated and decompensated types based on the kinetics of the knee joint in the sagittal plane, as well as the stiff-knee associated crouch gait pattern [17-20].

A qualitative assessment of the difference between a decompensated crouch pattern and a stiff-knee according to graphs of the kinematics and kinetics of the joints is difficult. Quantitative criteria have not been reflected in the literature.

The **purpose** of the study was to conduct a comparative analysis of the quantitative parameters of the compensated, decompensated and stiff-knee crouch patterns.

## MATERIALS AND METHODS

The locomotor profile was assessed by video computed gait analysis (CGA) in inpatient conditions in 27 children (54 limbs) with spastic diplegia, who had previously undergone fibromyotomies according to the Ulzibat method, open lengthening of the Achilles tendon. The mean age at the time of the survey was 13.0 (8-17) years. The control group consisted of 19 children without orthopedic pathology (38 limbs) of similar age. The subjects underwent computer analysis of walking parameters in the gait analysis laboratory of the Ilizarov Center (Ilizarov Gait Analysis Laboratory). Patients walked with the use of additional support, barefoot on a 7-meter track at their usual speed. Children of the control group walked barefoot at a speed close to the speed of patients, which they regarded as a slow pace of walking.

There are three groups of lower limb movement disorders within the crouch gait pattern:

Group I – crouch gait pattern of "compensated type", included 30 cases;

Group II – crouch gait pattern of "decompensated type", included 14 cases;

Group III – stiff-knee crouch gait pattern, included 10 observations.

Kinematic data were recorded by Qualisys 7+ optical cameras (8 Qualisys cameras) with the passive marker video capture technology and synchronized with six dynoplatforms KISTLER (Switzerland). For installing the markers, the IOR model was used, which is optimal with a minimum system configuration and is suitable for analyzing walking of the subjects whose speed is low [21]. The technical markers were removed after calibration, and the subject was asked to walk in the calibrated volume until at least 10 walking trials had been completed. No instructions were given regarding foot positions. The patterns of the locomotor profile adopted by the Delphi Convention were analyzed [22]. The analysis of kinematics and kinetics was carried out with the QTM (Qualisys) and Visual3D (C-Motion) software programs with automated calculation [23]. The variables of kinematics and kinetics were exported and processed with the calculation of the total (for the hip, knee and ankle joints) positive and negative power [24]; total general peak power which is the sum of the absolute values of positive and negative power; useful peak power values which is the difference between the absolute values of positive and negative power values on the kinetics graphs. The overall mechanical efficiency, defined as the ratio of the positive (useful) peak power to the total one [25].

Statistical data processing was carried out using the Microsoft EXCEL-2010 data analysis package, supplemented by the developed by I.P. Gaidishev (2004) [26] nonparametric statistics and estimates of the normality of the distribution of samples *AtteStat*. The assessment of the normality of the distribution was carried out according to the criteria of asymmetry, kurtosis by Kolmogorov-Smirnov. Considering the fact that the function of distribution in the control group was normal, while data in the patients had a distribution other than normal, and the number of cases in the groups was from 10 to 30, nonparametric statistics were used to process the results with a significance level of $p \leq 0.05$. Quantitative characteristics of sample sets are presented in the tables as a median with a level of distribution of percentiles of 25÷75 % and the number of cases (n) equal to the number of limbs. The statistical significance of differences was determined using the unpaired Wilcoxon test. The method of sigma deviations compared all obtained average values of the patients' parameters with the average values of healthy children.

The permission of the Ethics Committee of the Federal State Budgetary Institution Ilizarov NMRC for TO (minutes No. 2(57) dated May 17, 2018) was obtained for conducting the study. The studiy was carried out in accordance with the ethical standards of the Declaration of Helsinki of the World Medical Association "Ethical principles for medical research involving human subjects" as amended in 2000, "Rules of Clinical Practice in the Russian Federation", approved by Order of the Ministry of Health of the Russian Federation of June 19, 2003 No. 266. Parents of children participating in the study were present at the tests and confirmed informed consent to its conduct and publication of research results without identification.

## RESULTS

A qualitative picture of the kinematics, kinetics and power of the knee joint in different crouch gait patterns is shown in Figure 1.

The results of quantitative studies are presented in Tables 1, 2, 3

Relative to normal values, the Gait Profile Score (GPS) in patients with compensated, decompensated and “stiff-knee” crouch patterns deviated from the norm by 6δ, and in “stiff-knee” pattern it was significantly ($p = 0.0003$) higher than in the decompensated crouch pattern, which reflects its clinical significance in assessing the severity of the pathology. The parameters that did not have statistical differences in the groups include dorsiflexion position at the start of the stance phase, but this indicator deviated from the normal values in the “stiff-knee” group by more than 3.0δ; amplitude of the ankle joint movement, which deviated from the norm within 1.0δ; the duration of the stance phase of the gait cycle; the moment of maximum flexion of the knee joint in the swing phase of the gait cycle; hip flexion angle at the beginning of the stance phase. The maximum angle of hip extension and femur rotation in the stance phase of the gait cycle differed from the norm values within 1.0δ-5.0δ, but the difference was more expressed relative to “stiff-knee” pattern (Table 1).

*Parameters that had statistical differences in the groups* The angle of maximum dorsiflexion of the foot in the “stiff-knee” pattern deviated from the norm by 5.7δ to 38.7° (35.0 ÷ 45.9°) with a significant ($p = 0.0017$) difference from the compensated and decompensated crouch patterns, which deviated from the norm values only by 1.5δ and 1.1δ, respectively. The foot dorsiflexion in the swing phase of the gait cycle was also maximally expressed in the stiff-knee pattern with a significant difference ($p = 0.013$) from the decompensated crouch pattern. In these patterns, we recorded multidirectional rotation of the foot relative to the motion vector with a significant ($p = 0.040$) difference: it was pronounced external rotation of the foot in “stiff-knee” pattern, while in compensated and decompensated crouch patterns, it was close to normal with a deviation within 1.0δ. The angle of flexion and extension of the knee joint at the beginning of the stance period significantly ($p = 0.012$, $p = 0.00057$, respectively) increased with the severity of the pathology and in “stiff-knee” averaged: flexion 68.0° (58.6÷72, 7°), extension - 70.0° (44.4÷77.6°).

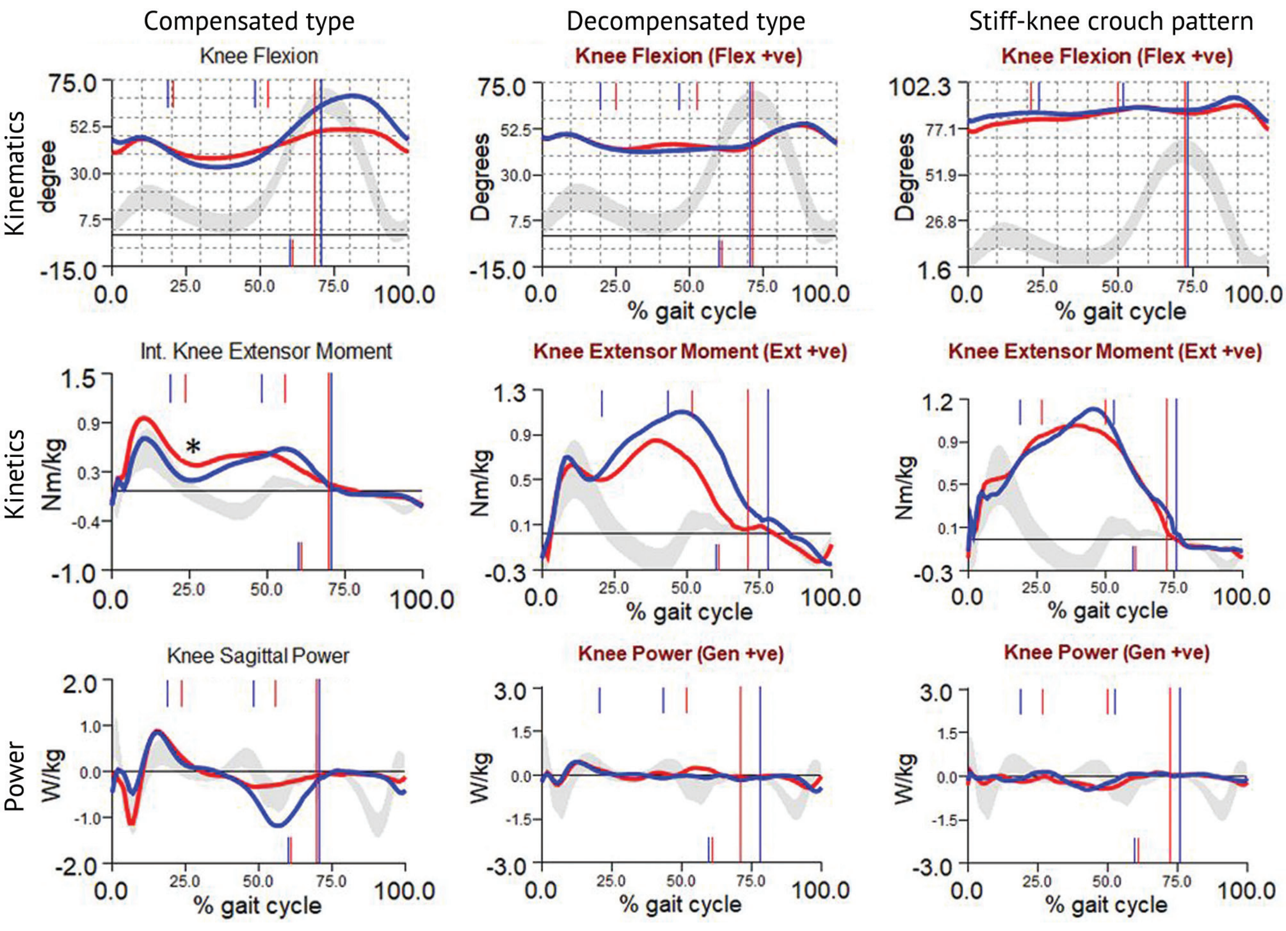


**Fig. 1** Graphs of kinematics, kinetics, power of the knee joint in crouch pattern of the "compensated" type, "decompensated" type, "stiff-knee" type

Table 1

Values of the kinematics of the lower limb joints in patients with cerebral palsy in **iatrogenic crouch gait** (Me (25 ÷ 75 %), M ± δ, n – number of limbs)

| Parameters | Norm | Walking with additional supports | | |
|---|---|---|---|---|
| | (n = 38) | Compensated type (n = 30) | Decompensated type (n = 14) | Stiff-knee crouch pattern (n = 10) |
| Age, years | 13.0 (10.0 ÷ 16.0) | 14.0 (12.0 ÷ 15.0) | 13.5 (10.2 ÷ 14.0) | 14.0 (11.0 ÷ 16.0) |
| Height, m | 1.58 (1.42 ÷ 1.60) | 1.49 (1.43 ÷ 1.53) | 1.50 (1.44 ÷ 1.55) | 1.45 (1.40 ÷ 1.55) |
| Weight, kg | 47.2 (34.2 ÷ 50.5) | 39.0 (33.1 ÷ 45.3) | 44.2 (37.6 ÷ 46.0) | 47.2 (37.3 ÷ 53.4) |
| Body mass index | 18.8 (15.9 ÷ 20.1) | 17.3 (16.8 ÷ 20.0) | 20.2 (16.5 ÷ 21.1) | 19.6 (17.7 ÷ 22.5) |
| % relative the sex/age norm | | 87.5 (83.4 ÷ 101.5) | 101.9 (84.4 ÷ 103.9) | 101.3 (86.9 ÷ 107.3) |
| Walking speed, m/sec | 0.64 (0.55 ÷ 0.68) | 0.60 (0.56 ÷ 0.70)<br>P* = 0.00002 | 0.61 (0.57 ÷ 0.61) | 0.65 (0.42 ÷ 0.69) |
| M ± σ | *0.62 ± 0.11* | *0.62 ± 0.12 (0 %)* | *0.58 ± 0.09 (36 %)* | *0.56 ± 0.14(54.5 %* |
| GPS | 8.8 (7.5 ÷ 9.3) | 16.0 (15.2 ÷ 18.2)<br>P▼ = 0.000000004 | 18.9 (17.4 ÷ 19.7)<br>P▼ = 0.000000017 | 26.3 (25.2 ÷ 28.9)<br>P▼ = 0.0000013<br>P** = 0.0003 |
| M ± σ | *8.33 ± 1.38* | *16.7 ± 2.31(606 %)* | *18.9 ± 1.66(766 %)* | *26.1 ± 2.94(1288 %)* |
| Angle of maximum foot dorsiflexion in stance phase, ° | 14.6 (11.5 ÷ 18.5) | 20.5 (17.7 ÷ 27.7)<br>P▼ = 0.0001 | 23.6 (17.7 ÷ 31.4)<br>P▼ = 0.0225 | 38.7 (35.0 ÷ 45.9)<br>P▼ = 0.0000013<br>P** = 0.0017 |
| M ± σ | *15.3 ± 4.23* | *21.8 ± 5.6 (153 %)* | *24.0 ± 7.87(205 %)* | *39.4 ± 1.89(569 %)* |
| Foot position at push off, ° | 10.1 (6.9 ÷ 12.0) | 18.3 (13.6 ÷ 24.1)<br>P▼ = 0.0000006 | 13.1 (9.1 ÷ 24.5) | 29.6 (24.8 ÷ 35.2)<br>P▼ = 0.0000017<br>P** = 0.013 |
| M ± σ | *9.87 ± 3.44* | *18.6 ± 6.3 (253 %)* | *17.1 ± 8.72(210 %)* | *29.3 ± 6.69(565 %)* |
| Angle of foot orientation relative to the vector of walking (max values), ° | 2.6 (-0.9 ÷ 8.7) | 5.4 (-7.0 ÷ 17.7) | 7.0 (-10.6 ÷ 19.0) | -11.3 (-20.8 ÷ -2.1)<br>P▼ = 0.00048<br>P** = 0.040 |
| M ± σ | *3.28 ± 6.89* | *4.5 ± 14.2 (17.7 %)* | *4.83 ± 15.3(22.5 %)* | *-11.4 ± 9.3(118 %)* |
| Ankle of knee flexion at the start of stance phase, ° | 9.5 (6.0 ÷ 11.0) | 42.0 (35.3 ÷ 51.5)<br>P▼ = 0.00000000001 | 48.8 (44.5 ÷ 52.4)<br>P▼ = 0.000000017 | 68.0 (58.6 ÷ 72.7)<br>P▼ = 0.0000013<br>P** = 0.012 |
| M ± σ | *8.93 ± 5.21* | *43.2 ± 9.68(657 %)* | *49.1 ± 6.73(771 %)* | *65.0 ± 9.88(1076 %)* |
| Angle of peak knee extension in stance phase, ° | 9.6 (5.5 ÷ 13.5) | 26.3 (18.9 ÷ 44.2)<br>P▼ = 0.00000002 | 40.8 (37.1 ÷ 43.7)<br>P▼ = 0.00000002<br>P* = 0.0086 | 70.0 (44.4 ÷ 77.6)<br>P▼ = 0.0000013<br>P** = 0.00057 |
| M ± σ | *9.51 ± 7.0* | *29.6 ± 13.1(287 %)* | *42.7 ± 6.15(474 %)* | *67.9 ± 10.25(834 %)* |
| Range of knee extension | 2.6 (1.9 ÷ 5.0) | 15.8 (11.5 ÷ 20.3)<br>P▼ = 0.000000001 | 9.0 (6.7 ÷ 10.4)<br>P▼ = 0.00019<br>P* = 0.0023 | 2.9 (1.8 ÷ 5.8)<br>P*** = 0.0032 |
| M ± σ | *4.0 ± 3.37* | *15.7 ± 4.97(347 %)* | *9.23 ± 3.01(155 %)* | *3.84 ± 2.12(-4.7 %)* |
| Angle of maximum flexion in swing, ° | 57.9 (55.5 ÷ 63.0) | 64.2 (58.9 ÷ 68.1)<br>P▼ = 0.016 | 70.1 (57.7 ÷ 71.1)<br>P▼ = 0.00097 | 84.6 (76.9 ÷ 93.9)<br>P▼ = 0.0000017<br>P** = 0.0057 |
| M ± σ | *58.5 ± 5.43* | *62.7 ± 7.86(77.3 %)* | *67.1 ± 7.77 (158 %)* | *84.23 ± 8.73(473 %)* |
| Range of knee flexion | 48.5 (42.0 ÷ 53.0) | 33.4 (24.6 ÷ 41.9)<br>P▼ = 0.000009 | 23.4 (17.9 ÷ 29.3)<br>P▼ = 0.00000003<br>P* = 0.0023 | 11.6 (11.3 ÷ 20.1)<br>P▼ = 0.0000015<br>P** = 0.014 |
| M ± σ | *48.8 ± 7.70* | *33.2 ± 9.24(-203 %)* | *24.4 ± 6.16(-316 %)* | *16.3 ± 4.99(-422 %)* |
| Moment of maximum knee flexion in swing (% of gait cycle) | 72.0 (71.0 ÷ 73.0) | 84.0 (83.0 ÷ 86.0)<br>P▼ = 0.000000000002 | 84.0 (82.0 ÷ 85.0)<br>P▼ = 0.00000002 | 84.0 (82.2 ÷ 86.5)<br>P▼ = 0.0000013 |
| M ± σ | *72.0 ± 1.57* | *84.2 ± 2.26(777 %)* | *82.9 ± 2.86(694 %)* | *84.5 ± 2.3(796 %)* |
| Angle of femur flexion at the start of stance phase, ° | 26.5 (18.0 ÷ 29.5) | 40.3 (30.5 ÷ 44.0)<br>P▼ = 0.0000005 | 42.7 (34.1 ÷ 48.7)<br>P▼ = 0.000061 | 50.4 (43.9 ÷ 58.2)<br>P▼ = 0.0000017 |
| M ± σ | *25.3 ± 6.99* | *37.4 ± 7.49 (173 %)* | *41.7 ± 8.90(234 %)* | *50.4 ± 7.25(359 %)* |
| Maximum angle of femur extension in stance phase, ° | -2.7 (-10.0 ÷ 0.1) | 3.4 (-4.6 ÷ 10.6)<br>P▼ = 0.003 | 12.7 (4.9 ÷ 18.6)<br>P▼ = 0.00004 | 24.4 (12.7 ÷ 30.1)<br>P▼ = 0.0000013 |
| M ± σ | *-4.7 ± 6.53* | *1.65 ± 8.37 (97.2 %)* | *10.2 ± 8.48(228 %)* | *31.7 ± 9.14(557 %)* |

*Note*: reliability of differences in the unpaired Wilcoxon test is shown: P▼ – relative to the norm values, P* – decompensated and compensated crouch patterns, P** – decompensated and stiff knee crouch pattern.

Table 2

Kinetic values (N*m/kg) of the lower limb joints in CP patients with **iatrogenic crouch gait** (Me (25 ÷ 75 %), M ± δ, n – number of limbs)

| Parameters | Norm | Walking with additional supports | | |
|---|---|---|---|---|
| | (n = 38) | Compensated type (n = 30) | Decompensated type (n = 14) | Stiff-knee crouch pattern (n = 10) |
| Femur extension | 0.38 (0.27 ÷ 0.51) | 0.96 (0.71 ÷ 1.47) P▼ = 0.0000005 | 0.93 (0.60 ÷ 0.98) P▼ = 0.0017 | 1.0 (0.70 ÷ 1.35) P▼ = 0.0046 |
| M ± σ | *0.38 ± 0.16* | *1.07 ± 0.51 (431 %)* | *0.75 ± 0.31 (231 %)* | *0.92 ± 0.41 (338 %)* |
| Femur flexion | -0.38 (-0.46 ÷ -0.29) | -0.74 (-0.89 ÷ -0.47) P▼ = 0.000002 | -0.49 (-0.59 ÷ -0.37) P* = 0.0071 | -0.51 (-0.64 ÷ -0.36) P▼ = 0.039 |
| M ± σ | *-0.39 ± 0.13* | *-0.72 ± 0.25 (253 %)* | *-0.47 ± 0.16 (62 %)* | *-0.49 ± 0.18 (77 %)* |
| Tibia extension | 0.50 (0.36 ÷ 0.64) | 0.77 (0.57 ÷ 1.11) P▼ = 0.0000000003 | 0.69 (0.35 ÷ 0.77) P▼ = 0.000088 | 0.90 (0.73 ÷ 1.06) P▼ = 0.0000058 |
| M ± σ | *0.28 ± 0.16* | *0.88 ± 0.34 (375 %)* | *0.66 ± 0.27 (238 %)* | *1.07 ± 0.47 (494 %)* |
| Tibia flexion | -0.12 (-0.28 ÷ 0.05) | 0.03 (-0.12 ÷ 0.26) P▼ = 0.007 | 0.76 (0.38 ÷ 0.88) P▼ = 0.00000003 P* = 0.000024 | 0.95 (0.78 ÷ 1.35) P▼ = 0.0000013 |
| M ± σ | *-0.12 ± 0.21* | *0.08 ± 0.25 (95.2 %)* | *0.69 ± 0.27 (381 %)* | *1.16 ± 0.43 (610 %)* |
| Extension of tibia in preswing (push off) | 0.12 (0.06 ÷ 0.18) | 0.71 (0.39 ÷ 1.08) P▼ = 0.00000000007 | 0.82 (0.63 ÷ 1.1) P▼ = 0.000000017 | 1.22 (1.05 ÷ 1.86) P▼ = 0.0000013 P** = 0.014 |
| M ± σ | *0.14 ± 0.09* | *0.77 ± 0.35 (700 %)* | *0.88 ± 0.26 (822 %)* | *1.49 ± 0.53 (1500 %)* |
| Plantar flexion take-off force | 1.25 (1.15 ÷ 1.41) | 0.73 (0.59 ÷ 0.99) P▼ = 0.0000000009 | 0.84 (0.63 ÷ 0.99) P▼ = 0.0000007 | 0.83 (0.56 ÷ 1.22) P▼ = 0.0027 |
| M ± σ | *1.27 ± 0.19* | *0.77 ± 0.21 (-263 %)* | *0.81 ± 0.19 (-242 %)* | *0.85 ± 0.33 (-221 %)* |

*Note*: reliability of differences in the unpaired Wilcoxon test is shown: P▼ – relative to the norm values, P* – decompensated and compensated crouch patterns, P** – decompensated and stiff-knee crouch patterns.

Table 3

Values of peak power (W/kg) in lower limb joints in CP children in **iatrogenic crouch gait** (Me (25 ÷ 75 %), M ± δ, n – number of limbs)

| Parameter | Norm | Walking with additional supports | | |
|---|---|---|---|---|
| | (n = 38) | Compensated type (n = 30) | Decompensated type (n = 14) | Stiff-knee crouch pattern (n = 10) |
| **Knee joint**, generation | 0.21 (0.17 ÷ 0.26) | 1.07 (0.61 ÷ 1.66) P▼ = 0.0000000001 | 0.49 (0.33 ÷ 0.66) P▼ = 0.00007 | 0.55 (0.29 ÷ 0.82) P▼ = 0.00034 |
| M ± σ | *0.24 ± 0.11* | *1.15 ± 0.54 (827 %)* | *0.52 ± 0.19 (254 %)* | *0.58 ± 0.29 (309 %)* |
| **Knee joint**, релаксация | -0.46 (-0.58 ÷ -0.33) | -0.97 (-1.3 ÷ -0.81) P▼ = 0.000000005 | -0.76 (-0.89 ÷ -0.61) P▼ = 0.0000083 | -1.21 (-1.35 ÷ -0.99) P▼ = 0.000019 P** = 0.018 |
| M ± σ | *-0.47 ± 0.18* | *-1.11 ± 0.40 (355 %)* | *-0.77 ± 0.16(166.6 %)* | *-1.30 ± 0.45 (461 %)* |
| **Knee joint** (Knee Power), total general | 0.69 (0.57 ÷ 0.79) | 2.0 (1.54 ÷ 3.12) P▼ = 0.0000000003 | 1.02 (1.07 ÷ 1.57) P▼ = 0.00000013 | 1.75 (1.43 ÷ 2.29) P▼ = 0.000016 |
| M ± σ | *0.71 ± 0.23* | *2.26 ± 0.87 (501 %)* | *1.30 ± 0.28 (256 %)* | *1.88 ± 0.66 (508 %)* |
| **Ankle joint** push-off | 1.87 (1.42 ÷ 2.23) | 1.23 (0.84 ÷ 1.4) P▼ = 0.000001 | 1.32 (1.18 ÷ 1.58) P▼ = 0.00045 | 1.22 (1.67 ÷ 2.27) |
| M ± σ | *1.91 ± 0.63* | *1.16 ± 0.34 (-119 %)* | *1.28 ± 0.29 (100 %)* | *1.45 ± 0.78 (-73 %)* |
| **Total (general)** peak power of all limb joints | 3.36 (2.62 ÷ 3.68) | 5.54 (4.39 ÷ 6.87) P▼ = 0.000000003 | 3.97 (3.76 ÷ 4.29) P▼ = 0.0081 | 4.68 (4.0 ÷ 5.43) P▼ = 0.0054 |
| M ± σ | *3.28 ± 0.87* | *5.56 ± 1.20 (262 %)* | *3.89 ± 0.45 (70.1 %)* | *4.63 ± 1.19 (155 %)* |
| **Useful peak** power of all limb joints | 0.60 (0.46 ÷ 0.88) | 0.67 (0.14 ÷ 1.38) | 0.62 (0.38 ÷ 0.85) | 0.12 (-0.11 ÷ 0.39) P▼ = 0.0043 P** = 0.05 |
| M ± σ | *0.68 ± 0.35* | *0.78 ± 0.65 (28.5 %)* | *0.63 ± 0.34 (-14.3 %)* | *0.14 ± 0.43 (-154 %)* |
| **Mechanical efficiency**, % | 60.1 (57.9 ÷ 63.3) | 57.1 (51.4 ÷ 62.4) | 57.3 (54.8 ÷ 59.8) | 51.6 (47.0 ÷ 54.4) P▼ = 0.0000097 |
| M ± σ | *60.4 ± 4.04* | *57.1 ± 5.71 (-81.6 %)* | *57.7 ± 4.22 (-66.8 %)* | *51.5 ± 1.35 (-220 %)* |

*Note*: reliability of differences in the unpaired Wilcoxon test is shown: P▼ – relative to the norm values, P** – decompensated and stiff knee crouch pattern.

In the compensated crouch pattern, the angle of peak extension of the knee joint was lower than the angle of flexion of the knee joint at the beginning of the stance phase by 40 %; in the decompensated pattern it was by 17 % (p = 0.033); and the range of knee joint extension, on average, was 2.9°, significantly (p = 0.0032) lower than in the decompensated crouch pattern.

Among the parameters of kinetics, there was a significant difference in the groups: in terms of the force directed to the extension of the lower leg at the moment of the push off. In the "stiff-knee" pattern it was 40-50 % higher (p = 0.014) than in the decompensated crouch gait, and 70 % higher than in the compensated crouch pattern. The total (general) peak power of all joints of the limb does not have significant differences between groups and relative to the norm. However, the absolute negative values of the power of the knee joint are maximum, and the minimum useful peak power of the joints is reduced (p = 0.0043) by 80 % relative to the decompensated and compensated crouch patterns, the mechanical efficiency of work relative to the norm is significantly reduced by 15 % (p = 0.0000097) (Tables 2 and 3).

The analysis of the evaluation of gait patterns (compensated, decompensated and stiff-knee associated crouch gait patterns) revealed quantitative criteria of kinematics and kinetics in differentiating these patterns according to the parameters presented in Table 4.

Table 4

Differences between three types of iatrogenic crouch gait

| | Compensated crouch | Decompensated crouch | Stiff-knee |
|---|---|---|---|
| GPS | Up to 25.0 | Up to 25.0 | Up to 25.0 |
| Angle of maximum foot dorsiflexion in support phase | Up to 35.0° | Up to 35.0° | More than 35.0° |
| Range of knee extension | More than 11.0° | 6.0°-10.0° | Up to 6.0° |
| Range of knee flexion | More than 25.0° | More than 20.0° | Up to 20.0° |
| Power of tibia extensors in push-off | Less than 1.0 H* m/kg | Less than 1.0 H* m/kg | More than 1.0 H*m/kg |
| Power of tibia flexors in the midstance | Less than 0.25 H* m/kg | 0.26 – 0.75 H* m/kg | More than 0.75 H*m/kg |
| Negative knee joint power | More than -0.9 W/kg | More than -0.9 W/kg | Less than -0.9 W/kg |
| Useful peak power of joints work | More than 0.40 W/kg | More than 0.40 W/kg | Less than 0.40 W/kg |

## DISCUSSION

There are three types of movements within the crouch gait pattern [8, 19, 20].

**In the compensated crouch gait type**, the knee is not effectively loaded and is unloaded in the middle of the stance period (that is, the strength of the knee extensor is decreased), despite increased knee flexion during the stance period. This is usually achieved through tertiary deviations in the femur (increased flexion), pelvis (increased anterior tilt), and trunk (increased anterior tilt) [17, 19]. These tertiary compensatory deviations are possible with strong hip extensors (an increased and prolonged moment of the hip extensor is recorded). The compensated crouch gait is well tolerated when the child with cerebral palsy is young, small, light and strong. Rapid weight and height gain can cause knee flexion contractures, hamstring contractures, and gastrocnemius weakness.

**In the decompensated crouch gait type**, there are no tertiary compensatory deviations of the pelvis and trunk; the knee is not unloaded in the middle of the stance period (an increased moment of extension of the knee joint is maintained throughout the entire support phase), and a progressive overload of the knee extension mechanism is formed [19]. M. rectus no longer contributes to hip flexion in a closed chain. The tendon of the patella gradually lengthens, and the extensor mechanism weakens.

**There is also a stiff-knee associated crouch pattern**. Some authors believe that the "stiff-knee" crouch gait is a manifestation of the decompensated crouch gait pattern [18, 20], others refer it to an independent crouch gait pattern in the form of "stiff-knee gait", in which knee flexion in the swing phase is sharply limited, with time-delayed peak knee flexion [8, 27, 28]. The most commonly cited reason for the formation of this crouch pattern type is an excessive activity of m. quadriceps femoris throughout the entire walking cycle [29]. Another potential cause is reduced or ineffective push-off due to gastrocnemius weakness [30]. Stiff-knee gait can also result from already uncontrolled system dynamics, and not just deviations in muscle functioning or neurological control [20].

According to the kinematic data, the “stiff-knee” crouch gait pattern is formed both due to the knee joint, where spasticity of m. rectus is primary [31], hip profile is normal (peak hip power (PHP) ≥ 0.60 W/kg and registration time during the gait cycle (tPHP) ≤ 68 % of the gait cycle) [32], and the hip joint, where the main cause of selective motor control (SMC) impairment is weakness of the femur flexor muscles, and a decrease in the flexion moment and power of the hip joint is recorded [1, 33].

In contrast to published findings, our study managed to establish clear quantitative criteria for distinguishing these three types of the iatrogenic crouch gait pattern.

The main criterion for differentiating between these types of the crouch gait is the coordination of the work of the muscles – antagonists of the extensors/flexors of the lower leg. In the compensated case, the vector of ground force reaction (GRF) is shifted closer to the center of the knee joint, which unloads the knee in the mid-stance. Computer gait analysis reveals a decrease in the internal extensor moment of the knee and registration of the power parameters of the tibia flexors in negative values (-0.12÷0.26 H*m/kg). In the decompensated type and the “stiff-knee”type, the inclination of the trunk backwards maintains the force of the ground reaction beyond the center of the knee joint, which overloads the knee in the middle of the stance period. In this case, an increase in the extensor moment and the values of the power parameters of the leg flexors in positive values are recorded (0.38÷0.88 H*m/kg and 0.78÷1.35 H*m/kg respectively).

In normal walking, the index of antagonist extensors/flexors muscles of the lower leg is 4.1–12.0 relative units; in the compensated type, this indicator is not reduced, but in the decompensated and “stiff-knee” type, it is less than 1.0. According to the podography data, if the index of the lower leg antagonist muscles is more than 1.0, the asymmetry of the temporal and power parameters of the gait cycle is not expressed, while if the index of the lower leg antagonist muscles is less than 1.0, there are pronounced qualitative changes in the podograms, which correspond to a significant decrease in the functional activity of all muscles involved in locomotor action [34]. Quantitative criteria of kinematics and kinetics showed that the “stiff-knee” crouch pattern is a more severe pathology than the decompensated crouch gait: the flexion position of the thigh, lower leg and foot is more pronounced; the amplitude of extension in the knee joint is significantly lower and the indicator of the force directed to the extension of the lower leg at the moment of the push-off is higher, which is a quantitative criterion in differentiating these patterns. In normal walking, there is a compromise between the thigh and the lower leg. In these patients, the absolute values of the support push are significantly lower than the control normal values, on average, by 30 %, and the push-off walking is mainly created by the hip. The ratio of the values of ankle joint power generation and hip power generation [35] in all groups was reduced relative to the control, on average, by 80 %. The main function of the knee in the swing phase of the gait cycle is the formation of flexion-extension for lifting the foot, setting the foot and accepting the load at the next phase [36]. If the gait is without disorders, the main contribution to the kinetics of the knee joint is made by m. quadriceps femoris at the beginning of the support (stance) period and gastrocnemius muscles at the end of the support period. At a knee flexion angle of lower than 25º at the beginning of the stance period, the strength of the quadriceps femoris muscle does not exceed 1.0δ of the standard deviation from the mean value during normal walking [37].

In crouch gait, m. quadriceps femoris makes the main contribution to the kinetics of the knee joint throughout the entire stance period, and a positive strong correlation was found during the stance period between the average knee flexion angle and the average tibial extensor strength ($r^2$ = 0.97). If flexion position of the knee joint increases, an increase in the strength of the leg extensors during the stance phase in the crouch pattern is primarily associated with an increase in the strength of the quadriceps femoris muscle required to support the body ($r^2$ = 0.99) [38], and in the stiff-knee pattern, the strength of the extensor muscles of the lower leg is 30 % higher than in the decompensated crouch gait.

The hip moment curve had a relatively larger extensor moment due to the flexion position of the femur in all patients. On the graph of the knee joint kinetics, strong extensor moments were also recorded throughout the entire stance period of the gait cycle. The increase in the compensated and decompensated types had no significant differences, while in the “stiff-knee” it was significantly higher by 40–50 % (p = 0.014) than in the decompensated crouch gait. When the knee is held excessively flexed in the stance period, the ground force reaction vector (GRF) passes behind the knee and a sustained internal extension moment is created.

The power range of the knee joint during normal walking in adults is from 1.035 to 3.214 W/kg [39]. In our control group of children, at a walking pace of 0.62 ± 0.11 m/s, the power range of the knee joint was 0.69 (0.57÷0.79) W/kg, and in the entire gait cycle, the negative power of the knee is much higher than the generated power (positive power) [40], consistent with the literature data [41]. In all patients, the power range of the knee joint is increased due to negative values (negative power). Negative values of the segments of the joint power trajectory reflect physiological inhibition reflexes and pathological conditions of tissues (joint contractures, muscle spasticity, etc.), since the quadriceps femoris muscle contracts eccentrically in knee flexion, and energy transfer around the knee is inefficient [42]. In pathology and enhanced metabolic requirements during walking, an increase in absolute negative values was recorded on the kinetics graphs, which corresponds to an increase in metabolic requirements during walking [43]; in stiff-knee, the absolute negative values of the knee joint are greater, the useful peak power of all joints and the mechanical efficiency of work, respectively, are reduced. According to the literature, the total peak muscle power increases with an increase in the degree of weakness (negative power) of the muscles [44]. In our study, it is, on average, 45 % more in the stiff-knee pattern than in the decompensated crouch gait.

These characteristics should be used for planning surgical interventions and for determining the scope of the operation in relation to the choice between supracondylar extensor osteotomy and/or bringing down the patella. We believe that the latter procedure is sufficient for the compensated pattern and should be combined with extensor osteotomy for the decompensated type. In the stiff-knee associated pattern, reconstruction of the extensor apparatus should not be combined with distal transfer of the rectus femoris tendon. However, in this situation, gait analysis in the long-term period should be repeated. Thus, if stiff-knee gait due to full extension of the knee joint in the stance phase persists, the above transfer of the distal tendon m. rectus femoris on the flexors of the knee joint may be justified. Finally, we recommend using computer gait analysis as a rationale for timely intervention in the development of crouch gait - BEFORE the manifestation of the decompensated pattern.

## CONCLUSIONS

The crouch gait pattern in the absence of a tertiary compensatory deviation (trunk tilt) may develop either in combination or without a decrease in the power of the joints. Decompensated and compensated types of crouch gait have a significant difference in the kinematics of the knee joint and in the duration of the internal moment of extension. Moreover, the power parameters of the joints do not have significant differences. The stiff-knee associated crouch gait is the most severe type of the crouch pattern, when all power parameters of the joints are decreased. The manifestation of the severity of this pathological pattern may vary between the right and left limbs of the individual.

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