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Indicators of the kinetics of locomotor stereotypes in healthy children in different speed ranges of movement

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Abstract

Purpose To determine the normative values of the kinetic parameters of gait in healthy children in different speed ranges of movement. **Materials and methods** Locomotor profile assessment by video gait analysis (CGA) was performed on an outpatient basis in 27 children (54 limbs), aged 10–13 years. The following variables were used and processed: peak negative hip, knee and ankle power (W/kg) (relaxation); peak positive power of the hip, knee and ankle (support push) joints (W/kg) (generation); the total positive and total negative power was calculated(for the hip, knee and ankle joints); total peak power; net peak power values and overall mechanical efficiency. Kinetics indicators were generalized according to the ranges of ranking of the absolute walking speed (km/h), taking into account the weight of patients. Quantitative characteristics are presented in the table as a median, percentile range of distribution of values (25÷75 %) and the number of observations (n) equal to the number of limbs. **Results** The normative kinetic parameters of gait are presented at a speed of movement in the range from 1.1 to 5.0 km/h in healthy children aged 10–13 years. A strong correlation was found between the values of the power of the reference shock during the formation of the reciprocal inhibition reflex of the shin sprain and the speed parameters of movement (r = -0.925, n = 142 and p < 0.001). To change the speed of movement, the motor locomotor stereotype was changed with the redistribution of the load from one joint muscle to another. If the share of the contribution of the power of the muscles of the hip joint increased, on average, by 10.8 %, and of the knee joint – by 15.3 %, then the share of the contribution of the ankle joint decreased by 16.8 %. **Discussion** In locomotor stereotypes in the examined children, a significant positive correlation was found between walking speed and the total (r = 0.907, n = 104) and useful peak power (r = 0.475, n = 104) of the joint muscles, while the maximum median values of the useful total peak the power of all joint muscles was recorded at a speed of movement in the range from 3.1 to 4.0 km/h.

Keywords: children, walking stereotype, parameters, video analysis of gait

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INTRODUCTION

One of the main goals of gait analysis is to identify deviations in the patient's gait from "normal" movement patterns. Therefore, an important component of gait analysis is the availability of normative databases appropriate for a certain age and body constitution. The investigators of the children's gait used to create their own normative databases or refer to the published ones [1, 2]. The literature presents the temporal normative parameters of the gait cycle in both adults and children (Table 1).

In fact, the speed with which a person walks is determined by the parameters of the locomotor stereotype: kinematics of the joints, ground reaction force (GRF), moments of force and power of the joints, muscle activity and temporal characteristics of gait in children [2, 6], young adults [7], as well as in the elderly [8]. For the working-age population, very slow walking requires various neuromuscular, locomotor, postural and dynamic balance controls [9], and in contrast to kinematics, gait kinetics showed a strong relationship with walking speed and, in particular, with correlation coefficients greater than 0.90 for moments of flexion and extension [10] of the knee.

Table 1

Temporal parameters of the normal gait cycle [3, 4, 5]

	7–8 years	10–11 years	13–15 years	20–25 years
Walking speed, m/sec	1.05 ± 0.02	1.11 ± 0.02	1.12 ± 0.02	1.17 ± 0.03
Length of stride, m	1.04 ± 0.02	1.15 ± 0.02	1.26 ± 0.02	1.42 ± 0.02
Duration of stance phase, *% from duration of gait cycle*	62.0 ± 1.6	61.6 ± 0.9	62.8 ± 1.6	62.7 ± 1.1
Duration of swing phase, *% from duration of gait cycle*	38.0 ± 0.5	38.4 ± 0.7	37.2 ± 0.6	37.3 ± 0.6
|Duration of gait cycle, sec	0.99 ± 0.02	1.04 ± 0.01	1.13 ± 0.03	1.21 ± 0.03
Walking rate, steps/min	121 ± 2	115 ± 1	106 ± 2	99 ± 2
Double support time, *% from duration of gait cycle*	10.2 ± 0.7	12.1 ± 0.9	12.7 ± 0.4	12.7 ± 0.4

In healthy children, examined without taking into account walking speed, from 6 to 49 % of gait cycles were classified as abnormal for normative kinematic curves depending on the norm classifiers used (UNB or San Diego), respectively [11]. Neuromaturation of gait patterns occurs from age four, and speed is a reliable indicator of gait maturation. The speed characteristics of the gait are provided by different temporal parameters of the locomotor stereotype, kinetics (findings of the reference push), and kinematics taking into account the normalized speed [12] in children aged 4–17 years [6]. The given norms of plantar flexion force in children are given without specifying age, walking speed (1.27 N*m/kg) and muscle contraction power to perform the work of movement in the ankle joint, a support push (2.27 W/kg) [13]. Gender differences do not appear in children until neurological and musculoskeletal maturity, while the child's gait will continue to change, in terms of spatiotemporal parameters, until they reach their final anthropometric parameters [14].

Compared to adults, children show lower voluntary muscle strength, speed, and power even after adjusting for age-related size differences [15]. One likely explanation for these differences is the lower level of maximum voluntary muscle activation in children [16], which is associated with their relative inability to recruit or use their "fast twitch" type II motor fibers [16].

Despite the fact that some attempts to publish normative parameters of gait kinetics in adults have already been made [17], the speed characteristics of walking were determined very approximately and only subjectively: slow pace, normal pace, fast pace.

In a typical analysis of locomotor stereotypes, the gait patterns of people with pathologic walking at a comfortable pace are compared with a group of healthy people. However, since people with pathology tend to walk more slowly, this comparison may not be correct.

Thus, the normative parameters of gait kinetics depending on walking speed are of reasonable importance for physicians who rely on the results of gait analysis when optimizing patient treatment tactics [18–21]

Purpose of the study was to determine the normative values of the kinetic parameters of gait in healthy children in different speed ranges of movement.

MATERIAL AND METHODS

The locomotor profile was assessed by video gait analysis (CGA) on an outpatient basis in 27 children (54 limbs). The mean age at the time of gait analysis was 11.9 (10–13) years. The subjects underwent computer analysis of walking parameters at the Ilizarov Gait Analysis Laboratory. The children walked barefoot at a slow, habitual and fast speed on a 7-meter track.

Four groups were examined:

group I – walking speed 0.4÷0.7 m/sec (1.1÷2.0 km/h), included 38 subjects;

group II – walking speed 0.71÷1.2 m/sec (2.1÷3.0 km/h), included 40 subjects;

group III – walking speed 1.21÷1.5 m/sec (3.1÷4.0 km/h), included 44 subjects;

group IV – walking speed 1.51÷1.8 m/sec (4.1÷5.0 km/h), included 20 subjects.

Kinematic data were recorded by Qualisys 5+ optical cameras (6 cameras from Qualisys) with passive marker video capture technology; for kinetic data, one AMTI dynamic platform (BP600400, USA) was used. The IOR model was used for installing markers, which is optimal with a minimum system configuration and is suitable for analyzing not-fast walking of the subjects [22]. The patterns of the locomotor profile adopted by the Delphi Consensus were analyzed (Fig. 1) [23]. The analysis of kinematics and kinetics was carried out in the QTM (Qualisys) and Visual3D (C-Motion) programs with automated calculation of values [24]. The following variables were exported and processed: peak negative hip, knee and ankle power (W/kg) (relaxation); peak positive power of the hip, knee and ankle joints (support push) (W/kg) (generation); the total (for the hip, knee and ankle joints) positive and total negative power was calculated [25]; total general peak power as the sum of the absolute values of generation and relaxation; effective peak power values as the difference between the absolute values of generation and relaxation on the kinetics graphs [26]. Overall mechanical efficiency, defined as the ratio of positive (effective) peak power to the total.

Kinetics indicators were ranked according to the absolute walking speed (m/sec, km/h) and considering the patient's weight. All X-axis data were normalized to a percentage range from 0 to 100, which corresponded to a full gait cycle. Each gait cycle was highlighted, and average values were plotted on the graphs.

Statistical data were processed using the data analysis package Microsoft EXCEL-2010 and AtteStat. All kinetic parameters in the formula of their calculation include the variable speed of movement [17]. Taking into account the arbitrary regulation of the speed parameters of the gait cycle and the number of the subjects in the groups from 20 to 44, nonparametric statistics were used to process the results with a significance level of $p \leq 0.05$. Quantitative characteristics of samples are presented in the table as a median with a level of percentile distribution 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 permission of the Ethics Committee of the Federal State Budgetary Institution The Ilizarov Medical Research Center No. 2(57) dated May 17, 2018 was obtained. The studies were carried out in accordance with the ethical standards of the Declaration of Helsinki of the World Medical Association "Ethical principles for medical research involving humans" as amended in 2000, "Rules of Clinical Practice in the Russian Federation", approved by the Order Ministry of Health of the Russian Federation dated June 19, 2003, No. 266. The parents of the children participating in the study assisted the study tests, gave their informed consent to conduct it and to publish the results of the study without identifying the individuals.

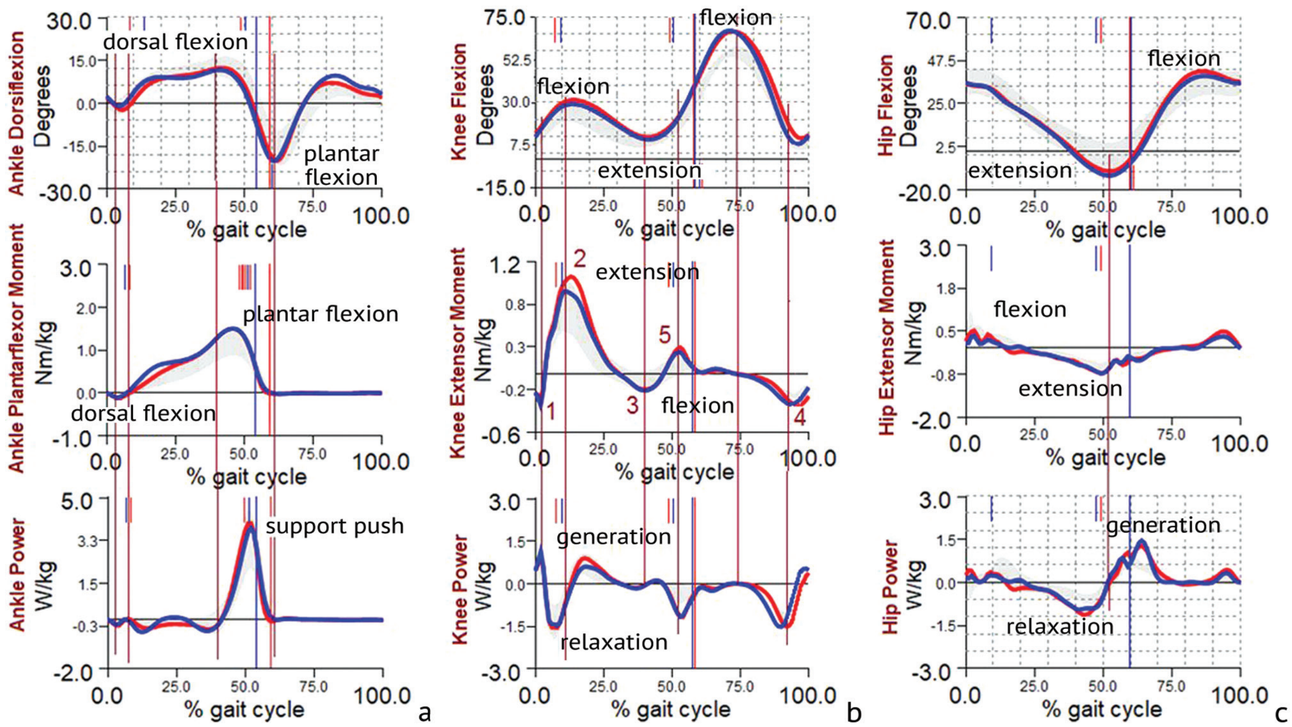

Fig. 1 Examples of patterns of kinematics and kinetics of the locomotor profile: a ankle joint; b knee joint, on the kinetics graph the selected N*m/kg values correspond to functional moments: 1 – absorption bending of the knee, 2 – extension of the lower leg, 3 – flexion of the lower leg, 4 – stretch reflex, 5 – end of foot roll (support push); c hip joint

RESULTS

The results of tests are presented in Tables 2, 3 and in Figures 2, 3, 4.

With an increase in walking speed from 1.0 to 5.0 km/h, statistically significant kinetic parameters are highlighted in Table 2. Dynamics of kinetic parameters (N*m/kg) with an increase in walking speed in the frontal plane for the knee and ankle joints, femur abduction, lower leg flexion is not statistically significant due to their large group and individual variability. This reflects the pronounced nonspecific nature of the participation of these muscle groups in the locomotor activity. Due to inertial forces, the values of the kinetics of the knee joint at the moment of heel-off are statistically unreliable.

The kinetic parameters of the muscles adducting the femur and the formation of the reciprocal inhibition of stretch reflex of the lower leg correlate most closely with the speed parameters of the gait (Pearson's correlation coefficient: r = -0.646, r = -0.925, respectively, at n = 142, p < 0.001).

In the range of walking speeds, increased from 0.4 to 5.0 km/h, the total general power of the joints increases by 3.4–5.7 times. The medians in the speed intervals were at 1.1–1.9 km/h – 33.36 (2.6–3.7) W/kg, at 2.0–3.3 km/h – 5.98 (4.9÷7.3) W/kg, at 3.4–4.1 km/h – 9.86 (8.9÷11.2) W/kg, at speed 4. 2–5.0 km/h – 13.5 (12.6÷14.9) W/kg (Table 3).

With an increase in walking speed from 1.0 km/h to 5.0 km/h, the value of the power of the support push increased by 3.0–3.5 times, the total power increased by 4.5–5.0 times (Table 3).

In typically developing children, a significant positive correlation was found between walking speed and the total general (r = 0.907, n = 104) and effective peak power (r = 0.475, n = 104) of joints work (Fig. 3).

Table 2

Kinetic findings (N*m/kg) of lower limb joints in children aged 10–13 years in relation to walking speed, Me (25 %÷75 %)

Parameters of the gait cycle	Walking speed (m/sec, km/h)			
	I (n = 38)	II (n = 40)	III (n = 44)	IV (n = 20)
	0.64 м/сек (0.4÷0.7) (1.1÷2.0 км/час)	**1.08 м/сек (0.71÷1.2)** (2.1÷3.0 км/час)	**1.44 м/сек (1.21÷1.5)** (3.1÷4.0 км/час)	**1.75 м/сек (1.51÷1.8)** (4.1÷5.0 км/час)
Hip extension	0.38 (0.2÷0.5)	0.69 (0.5÷0.8)	0.98(0.7÷1.2)**	1.36(1.17÷1.55)***
Hip flexion	-0.38 (-0.4÷-0.3)	-0.54 (-0.6÷-0.4)	-0.79(-0.9÷-0.6)**	-1.01(-1.24÷-0.76)***
Femur adduction	-0.04(-0.09÷-0.03)	-0.12(-0.20÷-0.06)*	-0.19(-0.2÷-0.1)**	-0.36(-0.49÷-0.22)***
Femur abduction	0.78 (0.7÷0.9)	0.84 (0.8÷1.0)	0.94(0.8÷1.0)	1.01(0.9÷1.1)
Absorption of knee bending	-0.12 (-0.18÷ -0.04)	-0.21 (-0.28÷-0.11)	-0.29(-0.4÷-0.15)	-0.39(-0.49÷0.31)***
Extension of the lower leg	0.27 (0.1÷0.5)	0.52 (0.3÷0.6)	0.85(0.6÷1.0)**	1.23(0.8÷1.3)***
Flexion of the lower leg	-0.12(-0.28÷0.05)	-0.13 (-0.24÷-0.02)	-0.16(-0.26÷-0.04)	-0.28(-0.39÷-0.15)
Stretch reflex	-0.08(-0.1÷-0.06)	-0.18 (-0.23÷-0.16)*	-0.29(-0.33÷-0.27)**	-0.38(-0.42÷-0.33)***
Moment of foot push-off	0.12 (0.06÷0.18)	0.16 (0.09÷0.26)	0.20(0.16÷0.27)	0.17(0.13÷0.20)
Knee abduction, varus	-0.03(-0.07÷-0.01)	-0.08(-0.1÷-0.03)	-0.07(-0.13÷-0.04)	-0.11(-0.21÷-0.04)
Knee adduction, valgus	0.31 (0.2÷0.4)	0.34 (0.2÷0.5)	0.41(0.2÷0.5)	0.42(0.3÷0.5)
Dorsal flexion, landing force	-0.07(-0.11÷-0.03)	-0.12 (-0.17÷-0.06)	-0.17(-0.18÷-0.13)**	-0.21(-0.24÷0.14)***
Plantar flexion, take-off force	1.25 (1.1÷1.4)	1.37 (1.2÷1.5)	1.52(1.4÷1.6)	1.61(1.55÷1.68)***
Eversion (varus) стопы	0.17 (0.1÷0.3)	0.31 (0.2÷0.4)	0.31(0.2÷0.5)	0.41(0.25÷0.49)
Inversion (valgus) стопы	-0.06(-0.1÷-0.03)	-0.08 (-0.1÷-0.05)	-0.07(-0.1÷-0.03)	-0.11(-0.1÷-0.06)

Notes: * – p < 0.05 between column II and I, ** – p < 0.05 between columns III and I, *** – p < 0.05 between columns IV and I

Table 3

Power peaks (W/kg) of joints in children aged 10–13 years in relation to walking speed, Me (25 %÷75 %)

Joints	Walking speed (m/sec, km/h)			
	I (n = 38)	II (n = 40)	III (n = 44)	IV (n = 20)
	0.64 m/sec (0.4÷0.7) (1.1÷2.0 km/h)	**1.08 m/sec (0.71÷1.2)** (2.1÷3.0 km/h)	**1.44 m/sec (1.21÷1.5)** (3.1÷4.0 km/h)	**1.75 m/sec (1.51÷1.8)** (4.1÷5.0 km/h)
Hip joint				
Generation	0.31 (0.2÷0.5)	0.86 (0.7÷1.1)	1.37(1.1÷1.6)	2.04(1.9÷2.6)
Relaxation	-0.26 (-0.3÷-0.2)	-0.55 (-0.8÷-0.3)	-0.91(-1.2÷-0.7)	-1.56(-1.9÷-1.1)
(Hip Power) total (general)	0.58 (0.4÷0.9)	1.40 (1.1÷1.9)	2.28(1.9÷2.8)	3.76(3.2÷4.3)
Effective power	0.08 (0.03÷0.18)	0.36 (0.14÷0.58)	0.35 (0.21÷0.51)	0.76 (0.25÷0.92)
Knee joint				
Generation	0.21 (0.1÷0.3)	0.44 (0.3÷0.7)	1.02(0.7÷1.3)	1.60(1.2÷2.0)
Relaxation	-0.46 (-0.5÷-0.3)	-0.96 (-1.2÷-0.7)	-1.81(-2.2÷-1.5)	-3.11(-3.8÷-2.8)
(Knee Power) (total)	0.69 (0.5÷0.8)	1.42 (1.0÷1.8)	2.86(2.1÷3.5)	4.84(3.8÷5.5)
Effective power	-0.25 (-0.38÷-0.10)	-0.42 (-0.69÷-0.31)	-0.76 (-1.10÷-0.55)	-1.78 (-2.24÷-1.17)
Ankle joint				
push-off generation	1.34 (1.0÷1.6)	2.54 (1.9÷2.8)	3.97(3.1÷4.5)	4.25(3.8÷4.6)
Relaxation	-0.56 (-0.6÷-0.5)	-0.66 (-0.8÷-0.5)	-0.75(-1.0÷-0.6)	-0.91(-1.0÷-0.6)
(Ankle Power) (total)	1.87 (1.4÷2.2)	3.14 (2.5÷3.6)	4.67(3.9÷5.5)	5.16(4.9÷5.6)
Effective power	0.81 (0.44÷1.08)	1.78 (1.35÷2.12)	3.12 (2.37÷3.63)	3.06 (2.44÷3.89)
Total peak power of all limb joints	3.36 (2.6÷3.7)	5.98 (4.9÷7.3)	9.86(8.9÷11.2)	13.5(12.6÷14.9)
Total effective peak power of all joints	0.60 (0.46÷0.88)	1.46 (1.12÷1.98)	2.65 (1.91÷3.23)	2.41 (1.21÷3.04)
Mechanical efficiency	60.0 % (57.9 ÷ 63.4)	63.0 % (59.4 ÷ 65.8)	63.5 % (60.6 ÷ 65.9)	58.9 % (54.7 ÷ 61.5)

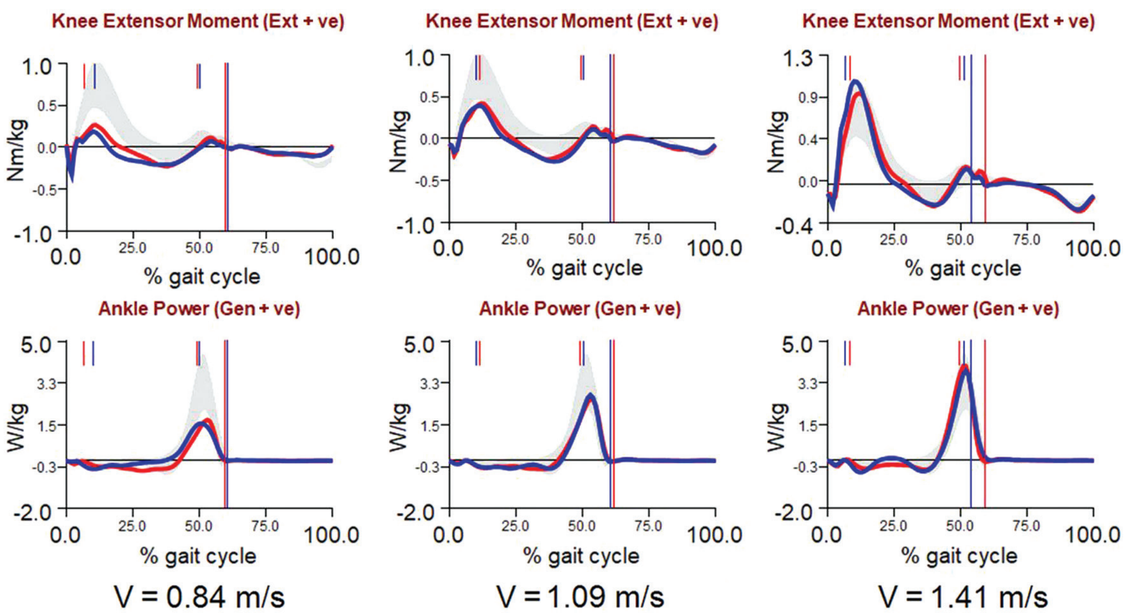

Fig. 2 An example of recording kinetics and kinematics in a healthy child K., 13 years old, walking at different speeds. The blue curve is the right limb, the red curve is the left limb. The gray curve is the normative parameters of QTM programs (Qualisys)

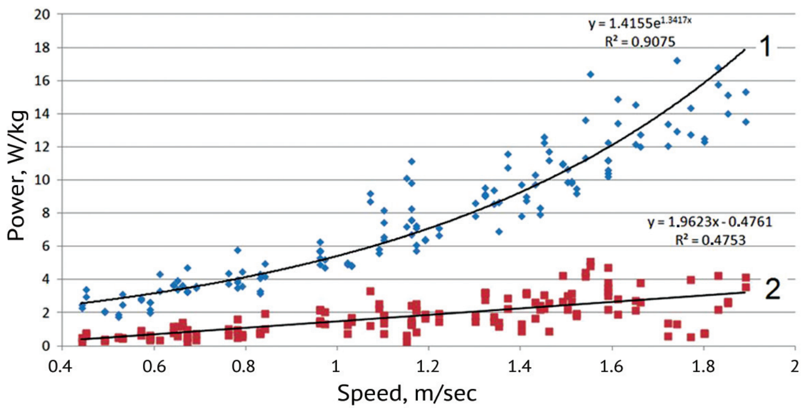

Fig. 3 Dependence of the total (1) and effective (2) peak power of the joints on the speed of walking

DISCUSSION

Strong correlation between the kinetic parameters of the muscles in the course of the reciprocal inhibition of stretch reflex of the lower leg with the speed parameters of the gait was revealed and is consistent with the literature data. Longer bundles allow an increase in the rate of fiber shortening. It has a direct effect on the rate of development of muscle power. Significant correlations ($r = -0.466$) were found between the length of the muscle bundle of m. gastocnemius and the rate of development of power and peak power in children with typical development, between the length of the muscle bundle of the knee extensor (m. rectus femoris) and the rate of development of power parameters ($r = 0.82$, $p < 0.001$), what was absent in children with cerebral palsy. The authors note that the regulation of the sarcomere length in walking is not similar in healthy children and children with cerebral palsy [27].

The reciprocal inhibition in stretch reflex due to the gamma motor neuron-reflex arc ensures the uniformity of muscle tissue contraction and the synergistic interaction of various muscle groups in the locomotor stereotype. The activity of the lower leg flexors begins in the non-support period of the gait and reaches the peak at ≈ 95 % of the gait cycle and continues at the beginning of the support period [3]. On the graphs of the kinematic and kinetic parameters of the knee joint (Fig. 1 a, point 4), the period and values of the formation of the reciprocal inhibition reflex of lower leg stretching correspond to the minimum values in the non-support phase of the gait cycle (95–98 % of the gait cycle). Premature activity (shift to values of 85–90 % of the gait cycle) occurs in patients with spasticity (stroke, multiple sclerosis, cerebral palsy), who have an increased stretch reflex, which prevents and limits knee flexion, reducing stride length [28]. On the EMG profile, the formation of stretch reflex of reciprocal inhibition of lower leg extension corresponds to the maximum activity of m. biceps femoris and m. semitendinosus [5].

The muscles of each joint on the kinetics graphs have negative (relaxation) and positive (generation) peak power values that are related to the work produced (generation) or dissipated (relaxation) by the skeletal muscles through either shortening (concentric) or lengthening (eccentric) contractions (Fig. 1). In walking on a flat surface, the body moves forward due to the release of accumulated mechanical energy in the process of physiological inhibition reflexes. Positive muscle work occurs during contraction, when the force and displacement vectors coincide, which increases mechanical energy. Negative values of kinetic trajectory segments reflect physiological inhibition reflexes and pathological conditions of tissues (joint contractures, muscle spasticity, etc.) [29, 30]. Effective power values were positive for the hip and ankle joints and negative for the knee joint (Fig. 4).

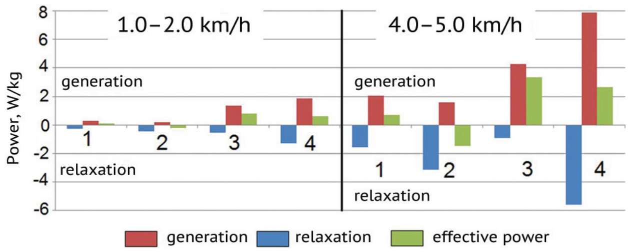

Fig. 4 Average peak power of the hip (1), knee (2), ankle (3) and total (4) at different walking speeds

Dissipation of energy to one degree or another occurs in all tissues of the body, but the muscles of the knee joint are the main dissipators of energy due to the formation of the main inhibitory reflexes there. This is confirmed by the close correlation between the kinetic values of the formation of the reciprocal inhibition reflex of tibia stretch and the speed parameters of the gait (Pearson's correlation coefficient: $r = -0.925$, $p < 0.001$). In case of pathology and an increase in metabolic demands by walking (joint contractures, muscle spasticity), an increase in absolute negative values is recorded on the kinetics graphs, which corresponds to an increase in metabolic demands during walking [31].

To increase the speed, the locomotor stereotype of gait changes with the redistribution of the load on the muscles of different joints. The share of the contribution of positive values of the peak power of the hip joint to the total peak power is on average: at a speed of 1.1-1.9 km/h – 17 %; at a speed of 2.0-3.3 km/h – 23.0 %; at a speed of 3.4-4.1 km/h – 23.1 %; at a speed of 4.2–5.0 km/h – 27.8 %, i.e. increases by 10.8 %. The share of the contribution of positive values of the peak power of the knee joint to the total peak power is on average: at a speed of 1.1–1.9 km/h – 20.5 %; at a speed of 2.0-3.3 km/h – 23.7 %; at a speed of 3.4-4.1 km/h – 29.0 %; at a speed of 4.2–5.0 km/h – 35.8 %, i.e. increases by 15.3 %. The share of the contribution of positive values of the peak power of the ankle joint to the total power is on average: at a speed of 1.1-1.9 km/h – 55.0 %; at a speed of 2.0–3.3 km/h – 52.5 %; at a speed of 3.4-4.1 km/h – 47.3 %; at a speed of 4.2-5.0 km/h – 38.2 %, i.e. decreases by 16.8 %.

To increase the speed of walking, the gait stereotype changes in such a way that the generation of power of the thigh muscles increases, and more energy is absorbed by the inhibitory reflexes of the knee joint, which is consistent with the literature data. This calculated indicator reached its maximum at the preferred gait speed [25]. Similar results of the contribution of generation and relaxation to the total power of the joints were obtained when examining healthy adults ascending and descending a ramp, stairs, and horizontal walking [32].

In typically developing children, the values of the correlation relationship between walking speed and the total general peak power significantly exceed the values of the correlation relationship between walking speed and the effective power of the joints (Fig. 3). The maximum median values of useful total peak power of all joints are recorded in this age group at a walking speed of 3.1–4.0 km/h, which indicates the optimality of the locomotor stereotype in this speed range.

In the structure of locomotor stereotypes, physiological inhibition reflexes play an important role and have a significant impact on their formation. Therefore, the analysis of kinetic parameters must consider the total general peak power of the joints. In pathologic conditions for diagnostic purposes, it is advisable to additionally consider the effective peak power.

CONCLUSIONS

The normative kinetic parameters of gait at different speeds of movement in the range from 1.1 to 5.0 km/h in healthy children aged 10–13 years have been shown.

A strong correlation was found between the kinetic parameters of the muscles by formation of the reciprocal inhibition in stretch reflex of the lower leg and the speed parameters of the gait ($r = 0.925$; $n = 142$ and $p < 0.001$).

An increase in the speed of movement (from 1.1 to 5.0 km/h) is accompanied by changes in the motor stereotype with redistribution of the load on the muscles of different joints: the share of the contributing power of the muscles of the hip joint to the total power increases, on average, by 10.8 %; of the knee joint by 15.3 %; and the share of the muscles of the ankle joint reduces by 16.8 %.

In the locomotor stereotypes in typically developing children, a significant positive correlation was found between walking speed and the total general (r = 0.907, n = 104) and efficient peak power (r = 0.475, n = 104) of the joint muscles. In the examined children, the maximum median values of the efficient total peak power of all joint muscles have been recorded at a walking speed of 3.1 to 4.0 km/h, what indicates the optimality and energy efficiency of the locomotor stereotype.

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