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Влияние ортопедической обуви на показатели межзонального распределения нагрузки на стопу при ходьбе больных детским церебральным параличом

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Обоснование. Как показывают клинические наблюдения больных спастическими формами детского церебрального паралича и опрос, наиболее часто используемым техническим средством реабилитации у таких пациентов является ортопедическая обувь. Вместе с тем практически отсутствуют клинические и инструментальные исследования ее влияния на биомеханику ходьбы.

Цель — определить влияние ортопедической обуви на межзональное распределение нагрузки по плантарной поверхности стопы при ходьбе детей с церебральным параличом с разными уровнями нарушения глобальных моторных функций (GMFCS).

Материалы и методы. Проведены биомеханические исследования 42 пациентов (возраст — от 5 до 16 лет) с детским церебральным параличом с уровнями GMFCS 1–3 при ходьбе в двух типах обуви — стандартной (то есть не влияющей на функциональность стопы) и ортопедической; также обследованы 14 человек контрольной группы в стандартной обуви (общее количество стоп — 112). Статистический анализ данных проведен с применением непараметрических методов в программе SPSS for Widows.

Результаты. Использование сложной ортопедической обуви у пациентов с уровнем GMFCS 1 привело к усугублению отклонения от нормы основных показателей взаимодействия стоп с опорой в виде уменьшения парциальной нагрузки на пятку, увеличения носочно-пяточного соотношения нагрузки, медиолатерального распределения нагрузки в области пучков. У пациентов с уровнем GMFCS 2 нормализующее влияние ортопедической обуви выявлено только по показателю медиолатерального распределения нагрузки в области пучков. У пациентов с уровнем GMFCS 3 нормализующее влияние ортопедической обуви обнаружено по большему количеству показателей распределения нагрузки на стопу.

Заключение. Исследование показало, что у детей и подростков с церебральным параличом использование сложной ортопедической обуви привело к наиболее значимой нормализации показателей межзонального распределения нагрузки под стопой у пациентов группы GMFCS 3, менее значимой — у пациентов группы GMFCS 2, к усугублению патологического отклонения показателей — у пациентов группы GMFCS 1.

Ключевые слова: медицинская реабилитация; детский церебральный паралич; GMFCS; ортопедическая обувь; биомеханика; ходьба.

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Influence of orthopedic shoes on the indicators of the interzonal load distribution on the foot when walking patients with cerebral palsy

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BACKGROUND: Clinical observations of patients with spastic forms of cerebral palsy and surveys showed the most commonly used technical rehabilitative device of this patient contingent are orthopedic shoes. However, almost no clinical and instrumental studies examine the effect of such shoes on the walking characteristics of patients with cerebral palsy (CP).

AIM: This study aims to estimate the effect of orthopedic shoes on the interzonal load distribution on the plantar foot surface in children with CP and adolescents with different levels of gross motor function disorders (GMFCS).

MATERIALS AND METHODS: Biomechanical studies were conducted in 42 patients with CP 5-16 years old with GMFCS 1–3 level while wearing standard and orthopedic shoes. In 14 healthy children controls while wearing standard shoes (a total of 112 feet). Biomechanical examinations were performed on the software and hardware complex "DiaSled-M-Scan" with matrix plantar pressure meters in the form of insoles. Statistical data analysis was performed using nonparametric methods via SPSS software for Windows.

RESULTS: The use of complex orthopedic shoes in patients with level GMFCS 1 did not improve but worsened their foot loading parameters. The shoes reduced the loading of the heel, increased the toe-heel load ratio, and mediolateral load distribution in the fascicle area. In patients with GMFCS 2, the positive effect of orthopedic shoes was limited to improving the mediolateral load distribution in the fascicle area. In patients with GMFCS 3, the positive effect of orthopedic shoes was noted in the majority of the tested parameters.

CONCLUSION: Thus, the study showed that in children and adolescents with CP using complex orthopedic shoes led to the most significant normalization of interzonal load distribution under the foot in GMFCS 3 patients, less significant — in GMFCS 2 patients, and worsened the parameters in GMFCS 1 patients.

Keywords: rehabilitation; cerebral palsy; GMFCS; orthopedic shoes; biomechanics; walking.

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BACKGROUND

Cerebral palsy (CP), which occurs in 1.5–3.0 per 1000 live births, is the most common cause of impaired gross motor functions in the pediatric population [1–3]. Disorders of motor functions, pathological changes in the stereotype of motor locomotions in patients with CP lead to self-care limitation, including independent movement and, as a result, to a decrease in the quality of life [4, 5].

One of the major clinical manifestations of CP is an impairment of the statodynamic function, in particular the interaction of the foot with the support [6, 7]. This pathological condition is corrected through a multidisciplinary approach [8, 9], which includes, along with surgical methods, conservative rehabilitation methods, such as orthotics and other technical means of rehabilitation [10–12]. In our clinical practice, complex or typical orthopedic shoes are often used for that purpose, which is provided to a significant number of children with spastic forms of CP [13]. This is also supported by the survey responses of the parents of these patients. However, to the best of our knowledge, this problem has not been sufficiently investigated and covered in scientific sources.

Most publications have described various orthoses for ankle joints (such as ankle foot orthosis [AFO], ground-reaction AFO, and leaf-spring AFO) as the most often used in the complex rehabilitation of patients with CP [14–16], and insoles, but not orthopedic shoes. Only one of these publications report on the role of orthopedic shoes in the correction of clubfoot in children with spastic forms of CP; however, they mainly emphasized on demonstrating the technical aspects of the manufacture of orthopedic shoes [17]. Most of the studies have considered the design aspects of the shoe, but not its influence on gait characteristics [18, 19].

Thus, there is an obvious discrepancy between the high frequency of prescribing orthopedic shoes to patients with CP, at least in Russia, and the insufficient clarification of this aspect in Russian and international sources. One of the main medical and technical requirements for such shoes is the normalization of the interzonal load distribution on the plantar surface of the foot and ensuring the rational participation of its various regions in rolling. In this regard, biomechanical studies have scientific and practical relevance in the analysis of the effect of orthopedic shoes on the load distribution over the zones of the plantar surface of the foot during walking in children and adolescents with CP.

This study aimed to determine the effect of orthopedic shoes on the interzonal load distribution on the plantar surface of the foot during walking in patients with CP having different levels of gross motor functions based on the gross motor function classification system (GMFCS).

MATERIALS AND METHODS

A one-stage observational experimental analytical controlled quantitative case–control study was carried out.

Study participants were divided into groups. The patient group (P) consisted of 42 individuals aged 5–16 years with confirmed diagnosis of CP, spastic diplegia or spastic CP, spastic tetraparesis with equino-plano-valgus, or planovalgus deformity of the feet, who were treated at the G.A. Albrecht Federal Scientific Center of Rehabilitation of the Disabled. The exclusion criteria were as follows: inability to walk independently or even with additional support (such as using crutches, canes, walkers, or with support from others), cognitive impairments that prevent contact with the patient for biomechanical examination, a history of botulinum toxin therapy less than 6 months before the examination, and a history of surgical treatment less than a year before the examination.

Group P was divided into three subgroups according to the level of impairment of gross motor functions based on the GMFCS [20]. Subgroups P1, P2, and P2 consisted of 7 patients with GMFCS level 1, 16 patients with GMFCS level 2, and 19 patients with GMFCS level 3, respectively.

The control group included 14 individuals aged 5–16 years without clinical signs of anatomical and functional disorders of the musculoskeletal system. This group included children examined during preventive examinations in educational institutions. The exclusion criterion for this group was the presence of cognitive impairments that prevent contact with the patient for biomechanical examination.

All biomechanical examinations were performed at the workplace, which included the DiaSled-M-Scan hardware-software complex (HSC) (joint production of the Russian companies DiaService and VIT) [21]. Baroplanthography (analysis of the load distribution over the plantar surface of the foot) was used in the system of the foot–shoe lodgment. Insole-shaped matrix sensors were inserted into the patient's shoes. Data were recorded while participants walked on a flat surface at a usual pace along a straight trajectory.

For each patient, examinations were performed in two stages, namely, walking using standard footwear (index "s") and walking using complex orthopedic shoes (index "o") on the same day. As requirements for construction, the standard footwear should include a flexible sole, soft top, absence of arching, 1-cm heel, and sufficient intra-shoe space.

Complex orthopedic shoes were purchased by relatives or guardians of patients before they were admitted to the hospital and should met special requirements, namely, made individually according to sizes or casts; contained a double-sided or circular rigid quarters as mandatory elements; used by the patient for at least 1 month and no more than 6 months; have sufficient intra-shoe space and did not lead to pains, plantar callosity, or roughness; and had no significant signs of deformation.

As a result of a biomechanical research, a database was formed that consisted of 196 cases, including one type of footwear (standard) for each foot in 14 individuals of the control group and two types of footwear (standard and orthopedic) for each foot of 42 patients with CP having gross motor function impairment of GMFCS levels 1–3.

Data analysis was performed using the SPSS for Windows software. Descriptive statistics, Kolmogorov–Smirnov test with the Lilliefors adjustment, and Shapiro–Wilk test with a critical level of significance $p = 0.05$, nonparametric Mann–Whitney test, and paired Wilcoxon test were used.

The study design is presented in Fig. 1.

RESULTS

When analyzing the distribution of pressure under the foot, the same division of the plantar surface of the foot was used, which is accepted in the DiaSled-M-Scan HSC software (Fig. 2).

The following are baroplanthographic variables analyzed as indicators of the interzonal load distribution under the foot:

1) f_heel — partial load on the heel area;
2) f_arch — partial load on the arch area;
3) f_fasc — partial load on the fascicle area;
4) f_fore — partial load on the forepart area;
5) Kfore/heel — forepart–heel load ratio;
6) Kf/r — ratio of loads on the front part (fascicles together with the forepart) and rear part (heel together with the sub-arch space) of the foot;

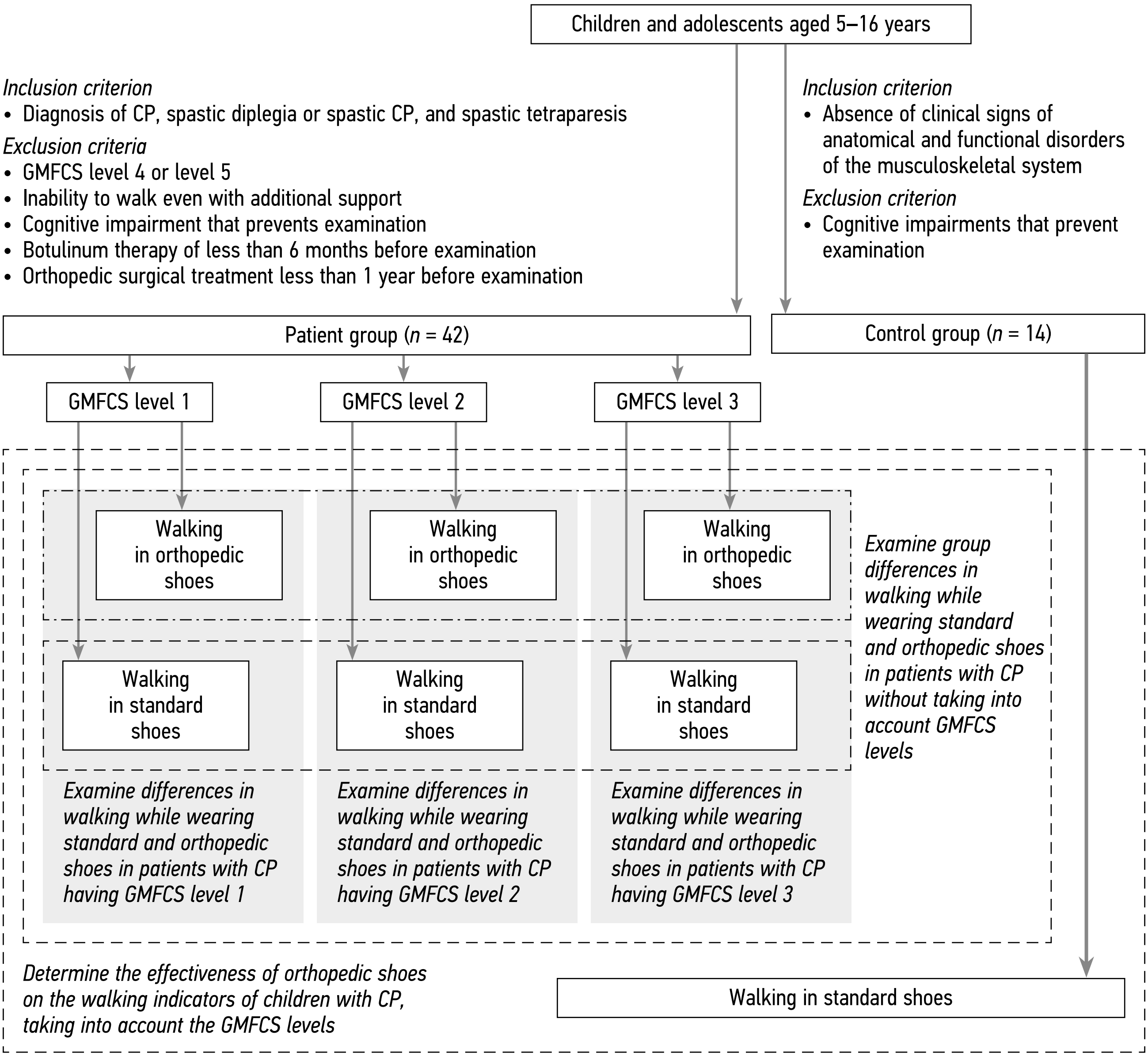

Fig. 1. Study design. CP, cerebral palsy

7) Km/l_heel — mediolateral load ratio in the heel area;
8) Km/l_arch — mediolateral load ratio in the arch;
9) Km/l_fasc — mediolateral load ratio in the area of the fascicles;
10) Km/l_fore — mediolateral load ratio in the forepart area;
11) Km/L — mediolateral foot load ratio.

The load on a specific area of the sensor (foot zone) was calculated as the sum of pressures on all sensor detector elements related to it (or parts of detector elements if they belong to several zones at once). The partial load on the foot area was defined as a fraction of the load on the entire foot. The forepart–heel ratio of the Kfore/heel load was calculated by dividing the forepart load by the heel load. The mediolateral load ratio in the foot area was calculated as the ratio of the load on the medial area of this region to the load on the lateral area.

To determine the distribution type of the signs of variables in the sets of cases obtained in the analysis while patients were walking, the Kolmogorov–Smirnov test with the Lilliefors adjustment and the Shapiro–Wilk test were applied, and the shapes of histograms and quantile diagrams were analyzed. In most of the 11 variables, the distribution was not normal. This applies to the sets of cases obtained when walking in both standard and orthopedic shoes. In this regard, nonparametric statistical methods were used for subsequent data analysis.

The nonparametric paired Wilcoxon test was used to search for group differences between walking in standard shoes and in orthopedic shoes. The levels of significance *p* of the differences in variables were 0.306 for f_heel, 0.092 for f_arch, 0.789 for f_fasc, 0.934 for f_fore, 0.871 for Kfore/heel, 0.507 for Kf/r, 0.020 for Km/l_heel, 0.000 for Km/l_arch, 0.000 for Km/l_fasc, 0.124 for Km/l_fore, and 0.681 for Km/l. As shown in this list, significant differences are found in the interzonal load distribution on the feet during walking in standard and orthopedic shoes for only 3 of 11 variables in patients with CP. All of them were related to the load distribution relative to the longitudinal axis of the foot, namely, the mediolateral ratio of the load in the area of the heel Km/l_heel, arch Km/l_arch, and fascicles Km/l_fasc.

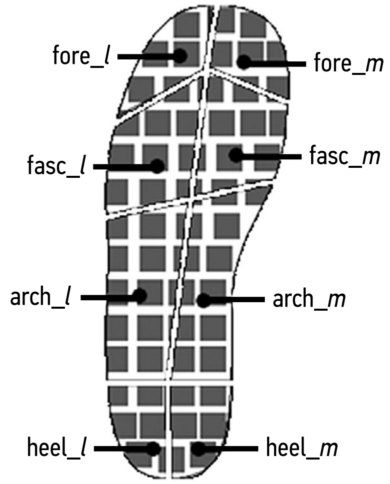

Fig. 2. Areas of the matrix measuring sensor: fore, forepart; fasc, fascicle part; arch, sub-arch; heel, heel part; *m,* medial; *l,* lateral zones

Table 1. Statistical characteristics of the variables, which revealed a significant difference in walking in orthopedic shoes compared with walking in standard shoes for the generalized group of patients with infantile cerebral palsy

Variable	Group	Q_1	Me	Q_2
Km/l_heel	Ps	0.64	0.85	1.10
	Po	0.67	0.92	1.20
Km/l_arch	Ps	0.52	0.72	1.11
	Po	0.57	0.90	1.30
Km/l_fasc	Ps	0.84	1.14	1.38
	Po	0.76	0.95	1.31

Note. Po, walking in orthopedic shoes; Ps, walking in standard shoes.

Despite the differences in three variables between the study groups, these results were not accepted as sufficient, since the analysis of the medians and percentiles of these variables showed a significant variation in values across the cases (Table 1). For example, when walking in orthopedic shoes (Po) for the Km/l_arch variable, the median value (0.90) differed by nearly a third from its value at the level of the first quartile Q_1 (0.57) and nearly two times from the value at the Q_2 level (1.30).

In view of such a pronounced data variation, a separate statistical analysis was performed for each of the three

Table 2. Significance of differences in walking using orthopedic shoes compared with walking using standard shoes in patients with cerebral palsy having varying degrees of impairment of gross motor functions (paired Wilcoxon test)

Comparison group	Level of significance of differences in the studied variables between the groups										
	f_heel	f_arch	f_fasc	f_fore	Kfore/heel	Kf/r	Km/l_heel	Km/l_arch	Km/l_fasc	Km/l_fore	Km/l
P1s and P1o	**0.011**	0.056	0.925	0.300	**0.019**	0.730	0.279	0.124	**0.025**	0.198	0.637
P2s and P2o	**0.047**	0.125	0.722	0.130	0.147	0.695	0.079	**0.015**	**0.001**	0.286	0.537
P3s and P3o	**0.046**	0.718	0.187	0.053	**0.006**	0.071	0.242	**0.006**	**0.002**	0.535	0.777

Note. Variables with significant differences are presented in bold typeface. P1, GMFCS 1 subgroup; P2, GMFCS 2; P3, GMFCS 3; o, orthopedic footwear; s, standard footwear.

Table 3. Median values of variables for which significant differences were revealed in patients with infantile cerebral palsy walking using orthopedic shoes compared with walking using standard shoes according to levels of impairment of gross motor functions

Groups of patients		Me (median) of variables			
		f_heel	Kfore/heel	Km/l_arch	Km/l_fasc
Control group using standard shoes		28.0	0.55	No significant differences were found (Table 2)	0.96
1.1 — patients with GMFCS level 1	1.1s — standard shoes	24.7	0.66		0.89
	1.1o — orthopedic shoes	20.6	0.82		0.77
Control group using standard shoes		28.0	No significant differences were found (Table 2)	0.69	0.96
1.2 — patients with GMFCS level 2	1.2s — standard shoes	18.2		0.77	1.20
	1.2o — orthopedic shoes	15.9		0.92	0.98
Control group using standard shoes		28.0	0.55	0.69	0.96
1.3 — patients with GMFCS level 3	1.3s — standard shoes	16.2	1.25	0.88	1.19
	1.3o — orthopedic shoes	17.2	0.99	0.96	1.03

subgroups of patients with different levels of impairment of gross motor functions. The results of this analysis are presented in Table 2.

The analysis showed that a significant difference in walking using standard versus orthopedic shoes in terms f_heel and Km/l_fasc is common for each subgroup of patients (with different levels of mobility impairment). In addition, differences were noted in Kfore/heel in subgroup P1, Km/l_arch in subgroup P2, and in both variables in subgroup P3. Table 3 shows the median values of these variables and only for GMFCS levels that were significantly different in the comparison of orthopedic shoes and standard shoes. To determine the nature of the influence of orthopedic shoes on walking of patients with CP, the median values of these four variables are presented in Table 3, not only for groups of patients with different levels of impairment, but also for the control group without anatomical and functional signs of impairment of the musculoskeletal system.

These tendencies are presented more clearly in quantile diagrams (Fig. 3).

DISCUSSION

This study characterized the interaction of the feet with the support in patients with CP. However, large data variations were obtained, which was not unexpected because all patients with CP were examined, regardless of the degree of deformity. Patients with different levels of impairment of gross motor functions have varying degrees of deformity of the musculoskeletal system and, as a result, have different walking patterns. Moreover, patients with GMFCS level 3, in contrast to other levels, used additional means of support (such as canes and walkers) while walking, which influence the walking stereotype [20]. At the same time, this data deviation was quantified to demonstrate the insufficiency of studying the interaction of the feet with its support in patients with CP without taking into account the level of GMFCS. Failure to take this provision into account can lead to errors because among the parameters used to analyze the interaction of the feet with the support, there are also parameters that decrease, deviating from the norm in a group of patients with one GMFCS level, and an increase in another group of patients, thus leveling the deviation of this parameter in the general group of patients with CP compared with the control group. For these reasons, to assess the effect of orthopedic shoes on the interaction of the feet with its support in patients with CP, the results of the statistical analysis should be used, taking into account the GMFCS level.

At all levels of impairment of gross motor functions, significant differences were registered in the partial load on the heel when walking using orthopedic shoes compared with walking using standard shoes (Table 2). For the groups with GMFCS levels 1 and 2, there was a decrease in the load on the heel, and for the group with GMFCS level 3, a minor increase was observed (Table 3, Fig. 3).

For patients with GMFCS level 1, a decrease in the partial load on the heel (Table 3) when walking using orthopedic shoes was accompanied by an increase in the forepart–heel load ratio (Kfore/heel), which indicates its redistribution from the heel to the forepart more than when walking using standard shoes and even more so with normal walking pattern. The pathological decrease in the mediolateral load ratio in the area of the fascicles, that is, a lateral displacement of the load in this area, was also even greater than that with standard footwear. Moreover, no significant difference in the mediolateral ratio of the load in the arch was revealed when walking in standard compared with walking in orthopedic shoes, which indirectly indicates mobility and/or insignificant severity of the planovalgus deformity of the foot. The position of the medial longitudinal arch in patients with mild motor impairments ensures the elevation of the lowered head of the talus without substantial resistance, forms the arch of

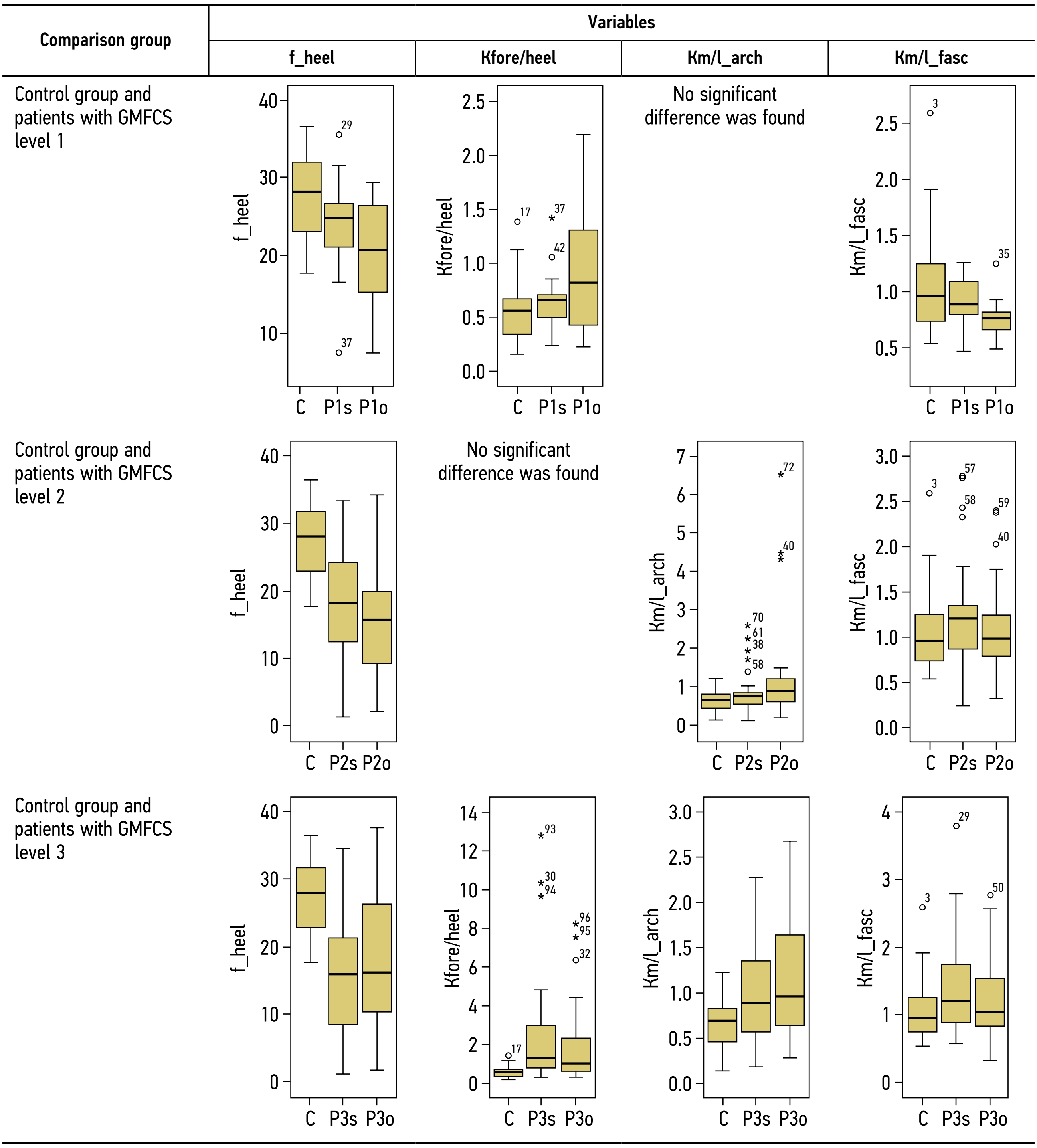

Fig. 3. Quantile diagrams of variables, which revealed a significant difference in the comparison of using orthopedic shoes and walking using standard shoes in groups of patients with different levels of impairment of gross motor functions: C, control group (in standard shoes); P1, GMFCS 1 subgroup; P2, GMFCS 2 subgroup; P3, GMFCS 3 subgroup; s, standard shoes; o, orthopedic shoes

the medial longitudinal vault, and thereby distributes part of the load over a substantial surface area of the foot.

Similarly, in the GMFCS 2 and GMFCS 3 groups, owing to the more pronounced and rigid deformity, the main part of the load in the midfoot was nearly on the head of the talus and the area of the talonavicular joint [22]. In this case, when using the position of the medial longitudinal arch, the foot rests on it; the load is localized in the area of the inner longitudinal arch, and the indicator of the mediolateral load ratio in this area increases, which is different from the norm, even more than with standard shoes.

The difference in the effect of orthopedic shoes on the amount of load in the heel area in different GMFCS groups can be explained as a consequence of the varying effects of these shoes on the correction of the foot arch. This conclusion was based on clinical cases that showed a difference in the possibility of correcting the equinus component of foot deformity in two cases, namely, 1) without preliminary correction of valgus deviation and discongruence in the talonavicular joint and 2) with the elimination of the valgus deviation of the rearfoot and stabilization of the midfoot. In case 1, the possibility of equinus correction is higher because of a decrease in the lever of the posterior muscle group [23], whereas in case 2, this possibility is lower because the Achilles tendon tension and the severity of the equinus component of the deformity increase during valgus correction [23, 24]. According to Mosca, this clinical test reveals the "true" equinus deformity of the foot, which is masked by the valgus component [24].

Thus, when using orthopedic shoes, we can assume the existence of a similar mechanism of the influence of the correction of equino-plano-valgus deformity of the foot on the biomechanics of rolling over.

If there was increased mobility in the transverse tarsal joint, in particular in the talonavicular joint (leading factor in the "planus" formation) and insignificant severity of foot deformity components, the use of orthopedic shoes (with placement of the medial longitudinal arch, rigid structure, and small intra-shoe space) leads to passive restoration of ratios in the talonavicular joint, formation of the medial longitudinal arch, and elimination of the valgus deviation of the foot. This entails an increase in the equinus component, which we indirectly recorded in the group of patients with GMFCS level 1 as a decrease in the load on the heel, an increase in the forepart–heel load ratio, and excessive lateralization of the load in the area of the fascicles (decrease in Km/l_fasc) when walking using orthopedic shoes compared with walking using standard shoes and even more so when compared with walking in the control group. In this case, the mobility of the foot ensures, owing to external factors, complete or even excessive correction of the medial longitudinal arch, which naturally shifts the load in the area of the fascicles outward laterally, but simultaneously reduces the load on the heel.

In patients with GMFCS levels 2 and 3, the foot deformity was more pronounced and rigid; therefore, with orthopedic shoes, they did not recover at all or the ratios in the joints of the middle and rear parts of the foot were restored partially passively; as a result, the equinus component was changed. Accordingly, in these groups, the differences in the heel load when using standard and orthopedic shoes are less significant when compared with those of patients with GMFCS level 1.

In patients with GMFCS level 3 walking in orthopedic shoes, the load distribution on the foot was normalized to some extent in the form of its increase on the heel and a decrease in the forepart–heel load ratio. There is also normalization (decrease) of the mediolateral load ratio in the area of the fascicles.

Medialization of the load in the fascicle area when walking using standard footwear is associated with the pathological position in the joints of the lower extremities [25], in particular with the presence of planovalgus deformity of the foot. Such deformities are less often observed in patients with GMFCS level 1 and are more pronounced in patients with GMFCS levels 2 and 3. Thus, in patients of these groups, (1) there was a pathologically altered mediolateral load ratio in the area of the fascicles and (2) the normalization of this indicator due to the use of orthopedic shoes with rigid special (corrective) elements is distinctive.

CONCLUSIONS

In patients with infantile CP having GMFCS levels 1–3 of gross motor functions impairment, significant differences were found in the nature of the effect of orthopedic shoes on the interaction of feet with a support.

In patients with GMFCS level 1, the use of complex orthopedic shoes led to an aggravation of disorders in the interaction of the feet with the support in terms of the main indicators, namely, the partial load on the heel, mediolateral distribution in the area of the fascicles, and forepart–heel ratio.

In patients with GMFCS level 2, the normalizing effect of orthopedic shoes on the interaction of the feet with the support was found only in the mediolateral distribution of the load in the fascicle area, and in patients with GMFCS level 3, similar effects were observed in a greater number of indicators of load distribution on the foot, both in the longitudinal and transverse directions (in the fascicle area) of the foot.

The use of complex orthopedic shoes led to the most significant normalization of the interzonal load distribution under the foot in patients with GMFCS level 3, less significant normalization in patients with GMFCS level 2, and aggravation of pathological deviations in the parameters of patients with GMFCS level 1.

This is a pilot study, and its results indicate the feasibility of conducting larger-scale studies, taking into account other indicators of the interaction of the feet with the support to determine the indications for the prescription of orthopedic shoes to patients with CP.

ADDITIONAL INFORMATION

Funding. The study received budgetary funding.

Conflict of interest. The authors declare no conflict of interest.

Ethical considerations. The study was approved by the ethics committee of the G.A. Albrecht Federal Scientific Center of Rehabilitation of the Disabled (Protocol No. 1 dated September 24, 2019) and was performed in accordance with the ethical standards of the Declaration of Helsinki. Patients and their representatives gave informed consent to participate in the study and publish its results.

Author contributions. *L.M. Smirnova* performed consulting assistance in instrumental biomechanical examinations, statistical processing of digital material, wrote the basic text of the article, and was involved in staged and final editing of the article. *A.A. Koltsov* created the concept and design of the study and performed staged and final editing of the article. *E.I. Dzhomardly* performed the literature analysis, conducted clinical examination and biomechanical examinations, created statistical forms, collected and processed the material, wrote the basic text of the article, and was involved in staged and final editing of the article.

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