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Rigidity of foot deformity in congenital clubfoot: foot stiffness index

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ABSTRACT

BACKGROUND: A unified system for assessing the severity of congenital clubfoot in newborns and young children worldwide remains to be established. "Rigidity" of foot deformity refers to the degree of "resistance" of foot tissues during manual correction of elements of the deformity and is often used in subjective severity of foot deformity assessment. However, there is no objective quantitative assessment for the degree of foot rigidity.

AIM: The study aimed to introduce a novel clinical sign — "rigidity of foot deformation", which enables objective assessment of the severity of foot deformity in congenital clubfoot.

MATERIALS AND METHODS: Before applying the first plaster cast, a clinical dynamometric examination was performed on 350 feet of 229 children, followed by a mathematical calculation of the foot rigidity index. Statistical analysis was performed using the nonparametric Mann–Whitney *U*-test and Spearman's rank correlation coefficient. Differences were considered significant at $p < 0.05$.

RESULTS: Significant differences were found in all clinical and dynamometric parameters between congenital clubfoot of I–II, III, and IV degrees ($p \leqslant 0.05$). Generally, the higher the degree of deformity, the more effort required to eliminate it, the smaller angle of simultaneous correction, and the higher index of foot rigidity. The results of Spearman's correlation analysis of clinical dynamometric examination indicators in children with congenital clubfoot of I–II degree may indicate the mobile nature of the foot deformity; III degree, a rigid version of the deformity; and IV degree, an extremely rigid degree of deformity.

CONCLUSIONS: Rigidity of the foot deformity is a crucial clinical sign that characterizes the severity of the foot deformity, which has a quantitative characteristic — the rigidity index. Initial data on foot rigidity enables objective assessment of the severity of the deformity and selecting an individual approach to its elimination when applying staged plaster casts using the Ponseti method.

Keywords: congenital clubfoot; degree of deformity; rigidity of deformity; rigidity index; Ponseti method; orthopedics; children.

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Ригидность деформации стоп при врожденной косолапости. Индекс ригидности стопы

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АННОТАЦИЯ

Актуальность. До настоящего времени в мире не существует единой системы оценки степени тяжести врожденной косолапости у новорожденных и детей раннего возраста. Классификации, объективно учитывающие ригидность деформации стоп и степень «податливости» тканей к редрессирующим усилиям, отсутствуют. Однако термин «ригидность» деформации стоп часто используют при субъективной оценке степени выраженности деформации стоп, вкладывая в его смысл степень «сопротивления» тканей стопы при ручной коррекции элементов деформации. При этом отсутствует объективная количественная оценка степени ригидности стопы.

Цель — ввести новый клинический признак — «ригидность деформации стоп», который позволит объективно оценить тяжесть деформации стоп при врожденной косолапости.

Материалы и методы. Перед наложением первой гипсовой повязки у 229 детей на 350 стопах было выполнено клинико-динамометрическое обследование с последующим математическим расчетом индекса ригидности стопы. Статистический анализ производили при помощи непараметрического *U*-критерия Манна – Уитни, коэффициента ранговой корреляции Спирмена. Различия считали достоверными при $p < 0,05$.

Результаты. При сравнении всех клинико-динамометрических показателей между врожденной косолапостью I– IV степени получены статистически значимые отличия ($p \leqslant 0,05$). Отмечается общая тенденция для пациентов с врожденной косолапостью независимо от степени тяжести: чем выше степень деформации, тем больше необходимо приложить усилий для ее устранения, тем меньше угол одномоментной коррекции и тем выше индекс ригидности стопы. Результаты корреляционного анализа Спирмена показателей клинико-динамометрического обследования у детей при врожденной косолапости I–II степени указывают на мобильный характер деформации стоп, при III степени — на ригидный вариант деформации, а при IV степени — на крайне ригидную степень деформации.

Заключение. Ригидность деформации стопы — это достаточно важный клинический признак, характеризующий степень выраженности деформации стопы, который имеет количественную характеристику — индекс ригидности. Определение степени ригидности перед началом лечения имеет важное практическое значение. Исходные данные ригидности стопы позволяют объективно оценить степень тяжести деформации и подобрать индивидуальный подход к ее устранению при наложении этапных гипсовых повязок по методу Понсети.

Ключевые слова: врожденная косолапость; степень деформации; ригидность деформации; индекс ригидности стопы; метод Понсети; ортопедия; дети.

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先天性马蹄内翻足的足部畸形僵硬。足部僵硬指数

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摘要

现实意义。迄今为止，世界上还没有一个统一的系统来评估新生儿和幼儿先天性马蹄内翻足的严重程度。目前还没有客观考虑足部畸形的僵硬程度和组织对矫正力的“柔韧”程度的分类方法。然而，足部畸形的“僵硬度”一词通常用于主观评估足部畸形的严重程度，其含义是指在手动矫正畸形元素时足部组织的“阻力”程度。同时，足部僵硬程度没有客观的量化评估。

本研究旨在引入一种新的临床体征——“足部畸形僵硬度”，从而使客观评估先天性马蹄内翻足部畸形的严重程度成为可能。

材料与方法。在使用第一个石膏绷带之前，对229名儿童的350只脚进行了临床和动力检查，然后用数学方法计算了脚的僵硬指数。统计分析采用非参数Manna WhitneyU标准和Spearman等级相关系数。当$p < 0.05$时，差异被认为是可靠的。

结果。在比较I-IV度先天性马蹄内翻足之间的所有临床和动力参数时，获得了具有统计学意义的差异（$p \leqslant 0.05$）。无论严重程度如何，先天性马蹄内翻足患者都有一个普遍的趋势：畸形程度越高，矫正所需的努力越大，单阶段矫正角度越小，足部僵硬指数越高。对I-II度先天性马蹄内翻足患儿的临床和动力检查参数进行斯皮尔曼相关性分析的结果表明，足部畸形具有活动性，III度为僵硬型畸形，IV度为极度僵硬型畸形。

结论。足部畸形的僵硬度是一个相当重要的临床表现，它是足部畸形严重程度的特征。这一体征有一个定量特征--僵硬指数。在开始治疗前确定僵硬程度具有重要的实际意义。根据足部僵硬度的初步数据，我们可以客观地评估畸形的严重程度，并在按照Ponseti方法进行阶段性石膏固定时，选择个性化的方法来消除畸形。

关键词：先天性马蹄内翻足；畸形程度；畸形僵硬度；足部僵硬度指数；Ponseti法；矫形；儿童。

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BACKGROUND

Congenital clubfoot is a common congenital malformation of the musculoskeletal system in children. Its incidence among the Russian population is within the average range, with a prevalence of 1–3 cases per 1,000 newborns [1, 2]. Evidence shows an increasing trend in the number of children born with congenital clubfoot [3].

Recently, a scientific paradigm shift has occurred in the treatment of congenital clubfoot. The conservative Kite technique and various surgical methods have been replaced by the Ponseti technique [4–9]. The Ponseti technique of deformity correction involves the gradual elimination of the main components of foot deformity, the use of plaster bandages, tenotomy of the shortened Achilles tendon, and the long-term wearing of corrective diverting splints [10–14]. The efficacy of manual correction of congenital clubfoot elements depends on the severity of pathological alterations in the capsular–ligamentous tarsal structures and tendon–muscular elements of the lower leg and foot. These pathological changes prevent the correction of the bone deformity and predetermine the degree of foot stiffness [15, 16]. Consequently, manual intervention should be used to overcome stiffness of pathologically altered soft tissue structures of the foot in congenital clubfoot to stretch these structures and restore anatomical relationships in the tarsal joints. Currently, no unified system has been established for assessing the severity of congenital clubfoot in newborns and infants. Conversely, several classifications of congenital clubfoot are known [18–20]. No objective classification system currently exists that considers the stiffness of foot deformity and degree of tissue pliability in response to corrective forces. Nevertheless, the term “stiffness” is frequently used in subjective assessments of the severity of foot deformities, with the degree of “resistance” of foot tissues during manual correction of deformity elements [21–24] being a key factor. However, there is currently no objective quantitative assessment for the degree of foot stiffness.

Therefore, the stiffness of the foot deformity in congenital clubfoot is a crucial clinical indicator that defines foot deformity severity and exhibits a quantitative attribute.

This study aimed to develop a novel clinical sign — stiffness of foot deformity — which enables the objective assessment of the severity of foot deformity in congenital clubfoot.

MATERIALS AND METHODS

Prior to initiating the Ponseti method of treatment, a comprehensive clinical and dynamometric examination was conducted on 350 feet of 229 children. According to the classification of congenital clubfoot by Dimeglio [18], mild (I) and moderate (II) degrees of the deformity severity were identified in 52 children (80 feet), severe (III) degree in 105 (160 feet), and extremely severe (IV) degree in 72 (110 feet). The forces required to correct the deformity were determined using a PCE-FB 200 dynamometer (Germany), which has a force measurement range of 20–200 N, with a resolution of 0.05 N.

Dynamometric indicators were measured according to the following procedure. The child is positioned on the back with the limb bent at a 90° angle at the knee and hip joints. One angle gauge bar is placed and fixed along the axis of the tibia, and another is positioned on the dorsal surface of the foot in the projection of the first toe gap, with the hinge axis of the angle gauge located in the talonavicular joint (Fig. 1).

When the internal rotation of the foot is eliminated, the forefoot and angle gauge on the dorsal surface of the foot are displaced simultaneously. The researcher secures the foot with one hand and places the thumb in the area of the

Fig. 1. Setting the center of the goniometer in the talonavicular joint
Рис. 1. Установка центра угломера в проекции таранно-ладьевидного сустава

Fig. 2. Fixing the force (Newton) on the dynamometer display when correcting deformity
Рис. 2. Фиксация усилия в ньютонах на дисплее динамометра при коррекции деформации

head of the talus bone. With the other hand, which is holding the dynamometer, the researcher places its stop in the area of the metatarsophalangeal joint and exerts pressure on the forefoot, thereby eliminating deformation with a force of 4 N (Fig. 2). Once the force reaches 4 N, as indicated on the dynamometer, further deformation correction is stopped. The achieved deformation correction angle at a force of 4 N is determined with the angle meter scale. The measurements are repeated to ensure accuracy. The values obtained during the examination are used to calculate the foot stiffness index (FSI). FSI is the ratio of the value of the applied force (4 N) to the achieved value of elimination of internal rotation of the foot relative to the tibia axis in degrees. It is calculated using the following formula: FSI = $4N/Y$, where $4N$ is the 4 N force applied to eliminate the deformity and Y is the value of the achieved elimination of internal rotation of the foot relative to the tibia axis in degrees with a 4 N force. A force of 4 N is appropriate in assessing the condition of the foot in children with congenital clubfoot and excludes the possibility of damaging effects on the soft tissue and bone structures of the foot during redressing. Moreover, it is sufficient to determine the state of the foot tissues by the angle of correction of internal rotation of the foot in patients with congenital clubfoot of I–IV degrees of severity.

Statistical analysis was conducted using the Statistica 12.0 software package. The normality of distribution was verified using the Kolmogorov–Smirnov and Lilliefors criteria. The Mann–Whitney *U* test was employed to compare the clinical and dynamometric examination parameters in children with congenital clubfoot of varying degrees of severity. The Spearman rank method was used to determine correlations between clinical and dynamometric parameters in congenital clubfoot. $P < 0.05$ indicated significant differences.

RESULTS

Prior to the initial application of plaster cast in 350 feet of 229 children, a clinical and dynamometric examination was conducted to determine the angle of deformity correction at a force of 4 N, followed by a mathematical calculation of the FSI using the formula. Table 1 presents the results of an intergroup comparison of the index of achievable deformity correction at 4 N and FSI in children with congenital clubfoot of I–IV severity before treatment.

Data analysis (Table 1) showed that the achievable correction in degrees at a force of 4 N in patients with congenital clubfoot of I–II degree was 26.64° ± 6.11°, whereas in those with a III degree, it was 22.13° ± 6.27°. Furthermore, a significant difference was observed between the two groups ($p = 0.001$). The index of the achievable correction in degrees at a force of 4 N during deformity correction in patients with congenital clubfoot of the IV degree was 13.80° ± 5.68°. A significant difference ($p = 0.001$ in both observations) was found in the intergroup analysis with the indexes for congenital clubfoot of I–II and III degrees.

The FSI value in patients with congenital clubfoot of I–II degrees was 0.15 ± 0.04, and in patients with III degree, it was 0.20 ± 0.06. A significant difference was noted when comparing patients with congenital clubfoot ($p = 0.001$). The FSI in patients with a IV degree deformity was the highest (0.30 ± 0.06) and was statistically higher in intergroup comparison with the indicators in congenital clubfoot of I–II and III degrees ($p = 0.001$ in both groups).

The clinical and dynamometric examination of the feet revealed regularities. For patients with congenital clubfoot of any degree of severity, when applying a force of 4 N during deformity correction, a general trend was observed: the higher the degree of deformity, the smaller the deformity correction angle and the higher the FSI. This difference

Table 1. Comparative analysis of clinical and dynamometric examination parameters of patients with congenital clubfoot of varying severity
Таблица 1. Сравнительный анализ показателей клинико-динамометрического обследования пациентов с врожденной косолапостью разной степени тяжести

Index under study	I–II degrees, $n = 62$ (80 feet), $M \pm SD$	III degree, $n = 105$ (160 feet)		IV degree, $n = 72$ (110 feet)	
		$M \pm SD$	p-level	$M \pm SD$	p-level
Deformation correction in degrees at a force of 4 N	26.64 ± 6.11	22.13 ± 6.27	0.001*	13.8 ± 5.68	0.001*,**
Foot stiffness index	0.15 ± 0.04	0.20 ± 0.06	0.001*	0.30 ± 0.06	0.001*,**

Note. M — average; *SD* — root mean square standard deviation, indicating the spread of data over the interval of the characteristic value relative to the average.
*Level of significance (Mann–Whitney test) of differences in relation to indicators of clubfoot of I–II degrees ($p \leq 0.05$); **level of significance of differences in relation to indicators of class III clubfoot.

Примечание. M — среднее; *SD* — среднеквадратичное стандартное отклонение, указывающее на разброс данных по интервалу значения признака относительно среднего.
*Уровень достоверности (критерий Манна – Уитни) различий по отношению к показателям косолапости I–II степени ($p \leq 0,05$); **уровень достоверности различий по отношению к показателям косолапости III степени.

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was significant in the intergroup comparison of the results of clinical and dynamometric examination of the feet in congenital clubfoot of I–IV degrees ($p \leqslant 0.05$). Table 2 shows the results of Spearman correlation analysis of clinical and dynamometric examination parameters in children with congenital clubfoot of I–II degrees.

The results of the Spearman rank correlation coefficient calculation showed no significant correlation between the FSI and angle of foot deformity correction at a force of 4 N. The Spearman rank correlation coefficient was 0.17, indicating that deformity correction occurs in a linear manner, with the foot retracting unimpeded and without significant resistance from its soft tissue structures. Table 3 displays the results of the Spearman correlation analysis of the clinical and dynamometric examination parameters in children with congenital clubfoot of III degree.

Furthermore, Table 3 illustrates that the correlation analysis revealed a moderate negative relationship between the FSI indices and angle of correction of foot deformity at a force of 4 N, with a rank correlation coefficient of –0.49. This shows that the higher the stiffness index of the deformity, the smaller the deformity correction angle when the deformity is corrected with a 4 N force. This result indicates that congenital clubfoot of III degree can be characterized as a rigid deformity, which is challenging to correct.

In congenital clubfoot of IV degree, the formation of classical correlations between clinical and dynamometric indicators was observed, which allowed for the characterization of this form of clubfoot as extremely stiff. According to data presented in Table 4, correlation analysis revealed a moderate negative relationship between the FSI and angle of foot deviation with a force of 4 N, with a rank correlation coefficient of –0.57. This indicates that the higher the stiffness index of the deformity, the smaller the angle of correction when the deformity is corrected with a 4 N force.

DISCUSSION

The criteria for the severity of foot deformity in congenital clubfoot remains unclear, and the definitions vary. Consequently, the Pirani scale, which evaluates six

Table 2. Spearman's coefficient of the angle of correction of foot deformity with a force of 4 N and the index of foot rigidity in children with congenital clubfoot of I–II degree

Таблица 2. Коэффициент Спирмена угла коррекции деформации стопы при усилии 4 Н и индекса ригидности стопы у детей с врожденной косолапостью I–II степени

Variables	Angle of foot deviation, in degrees	Foot stiffness index
Foot deformity correction angle at a force of 4 N	1.0	0.17
Foot stiffness index	0.17	1.0

Table 3. Spearman's coefficient of the angle of correction of foot deformity with a force of 4 N and the index of foot rigidity in children with congenital clubfoot of III degree

Таблица 3. Коэффициент Спирмена угла коррекции деформации стопы при усилии 4 Н и индекса ригидности стопы у детей при врожденной косолапости III степени

Variables	Angle of foot deviation, in degrees	Foot stiffness index
Foot deformity correction angle at a force of 4 N	1.0	–0.50*
Foot stiffness index	–0.50*	1.0

*Statistically significant ($p \leqslant 0.05$).
*Статистически достоверна ($p \leqslant 0,05$).

Table 4. Spearman coefficient of the angle of correction of foot deformity with a force of 4 N and the index of foot rigidity in children with congenital clubfoot of IV degree

Таблица 4. Коэффициент Спирмена угла коррекции деформации стопы при усилии 4 Н и индекса ригидности стопы у детей при врожденной косолапости IV степени

Variables	Angle of foot deviation, in degrees	Foot stiffness index
Foot deformity correction angle at a force of 4 N	1.0	–0.57*
Foot stiffness index	–0.57*	1.0

*Statistically significant ($p \leqslant 0.05$).
*Статистически достоверна ($p \leqslant 0,05$).

features in points (from 0 to 1), is commonly used for determining clubfoot severity. The features include a fold over the ankle joint, emptiness of the hindfoot, equinus, medial vertical fold on the foot, palpation of the head of the talus bone, and bending of the outer edge of the foot. Another evaluation system for congenital clubfoot is the Dimeglio classification [29–32]. This system allows for the determination of the severity of clinical signs, including the angle of equinus deformity, angle of varus deformity, angle of internal rotation of the foot, and angle of forefoot adduction. Based on the severity of each sign, points are assigned on a scale of 0–4. Additional points are allocated if a pronounced skin fold, cavus, or tibial atrophy is noted (1 point for each sign).

The present study used several combinations of the results of clinical examinations of the feet as the foundation for the aforementioned classifications. However, these classifications do not consider the severity of the stiffness of the deformity and are unable to measure the degree of tissue pliability to redressing forces.

A clinical and dynamometric examination was conducted to investigate the ability of foot tissues to resist corrective forces during manual correction of congenital clubfoot of varying degrees of severity according to the Ponseti method. Significant differences ($p \leqslant 0.05$) were observed when comparing all clinical and dynamometric indices between congenital clubfoot of I–IV degrees. Analysis of the results of clinical and dynamometric examination of the feet revealed regularities. A general trend is noted in patients with congenital clubfoot of varying degrees of severity when applying a force of 4 N during deformity correction. This trend can be described as follows: the higher the degree of deformity, the smaller the angle of correction and the higher the FSI.

The correlation between clinical and dynamometric parameters in congenital clubfoot has been established. The results of the Spearman rank correlation coefficients calculation in congenital clubfoot of I–II degrees exhibited no significant correlation between the FSI and angle of foot deformity correction at a force of 4 N (0.17). This indicates that the deformity correction is linear in nature, with an unimpeded retraction of the foot occurring without significant resistance from its soft tissue structures. Thus, in children with congenital clubfoot of I–II degrees, the foot deformity is mobile, based on the muscle component (imbalance) with minimal changes at the level of the capsule–ligamentous apparatus of the foot. Thus, clubfoot of I–II degrees can be considered mobile with predominant involvement in the pathological process of the muscular component that keeps the foot in the wrong position.

A moderate negative correlation was observed between the FSI and angle of correction of foot deformity at a force of 4 N in children with congenital clubfoot of III degree, with a rank correlation coefficient of –0.50. This demonstrates that congenital clubfoot of III degree can be characterized as a rigid deformity that is challenging to correct. The underlying pathology is primarily a pathologically altered capsule–ligamentous apparatus of the foot, with minor disturbances at the level of its osteoarticular structure.

In children with congenital clubfoot of IV degree, the results of Spearman correlation analysis indicated the presence of classical correlations between clinical and dynamometric indicators, which allow for the characterization of this form of clubfoot as extremely rigid. Moreover, the correlation analysis revealed a moderate negative relationship between the FSI and foot deviation angle with a rank correlation coefficient of –0.57. Notably, the character of foot deformity correction in congenital clubfoot of IV degree has common features with congenital clubfoot of III degree. However, the strengthening of correlations in congenital clubfoot of IV degree shows the extreme degree of its rigidity and stiffness, which significantly exceeds these characteristics in congenital clubfoot of III degree. Considering the distinctive characteristics of the correlations, it can be posited that congenital clubfoot of IV degree is a rigid deformity with a high stiffness index. This demonstrates that the stiffness deformity in congenital clubfoot of IV degree is underpinned by a combination of pronounced alterations in the capsular–ligamentous apparatus of the foot and significant disturbances at the level of the osteoarticular structure of the foot.

CONCLUSIONS

Stiffness of foot deformity is a significant clinical indicator that defines foot deformity severity. It should be quantified, and the stiffness index is an appropriate metric for this purpose. The FSI allows for the quantitative assessment of foot tissue state and determination of whether the deformity is rigid or pliable during manual correction of congenital clubfoot elements. Consequently, the stiffness index represents a fundamental quantitative indicator that characterizes the degree of foot deformity, considering its pliability to eliminate elements of congenital clubfoot during manual correction. The degree of stiffness should be determined before treatment. Initial data on foot stiffness allow for an objective assessment of deformity severity and an individual approach to its elimination when applying stage plaster casts according to the Ponseti method.

ADDITIONAL INFORMATION

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