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PES CALCANEUS DEFORMITY IN CHILDREN AND METHODS OF SURGICAL CORRECTION

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Introduction. *Pes calcaneus* deformity is a rare pathology in children, which is due to the defect of long flexors of the foot caused by various neurological diseases. The treatment choice is based on the patient's age, parameters of neuromuscular disorders, and degree of foot deformation.

Aim. This study aimed to analyze the results of operative correction of pes calcaneus deformities in children.

Material and methods. This analysis of surgical treatment involved 13 patients (21 feet) aged 1.5 to 15 years with *pes calcaneus* deformities. The different approaches and methods of surgical treatment were described. Children up to 12 years old were released joints of the foot with the elimination of deformation and tendon-muscle transposition with the transfer of functionally preserved muscles in the position of fallen muscle antagonists. Children over 12 years old underwent surgery on the bone apparatus of foot: three-articular arthrodesis or corrective osteotomy of the calcaneus, some cases were supplemented with tendon-muscle transpositions.

Results. Treatment results were evaluated based on the radiometric parameters on the system of AOFAS. All treated patients showed improvement in foot stability with reduced deformation; AOFAS at an average of 91.14 points was observed.

Conclusion. A record of all causes and strain components with a graded approach eliminates the *pes calcaneus* deformity in the long-term, despite persistent violation of neuromuscular conduction.

Keywords: *pes calcaneus*; neurogenic deformities of the foot; tendon-muscular transpositions; three-articular arthrodesis; osteotomy of the calcaneus; children.

ПЯТОЧНАЯ ДЕФОРМАЦИЯ СТОП У ДЕТЕЙ И МЕТОДЫ ХИРУРГИЧЕСКОЙ КОРРЕКЦИИ

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Введение. Пяточная деформация стоп относится к редко встречающейся патологии у детей, которая обусловлена поражением длинных сгибателей стопы вследствие различных заболеваний нервной системы. Выбор метода оперативной коррекции основан на возрасте пациента, параметрах нарушений нейромышечного аппарата, а также степени деформации стопы.

Цель исследования — анализ результатов оперативной коррекции пяточных деформаций стоп у детей в условиях нашего центра.

Материал и методы. Проведен анализ оперативного лечения 13 пациентов (21 стопа) в возрасте от 1,5 до 15 лет с пяточной деформацией стопы. Описан дифференцированный подход и методы хирургического лечения. Детям до 12 лет был выполнен релиз суставов стопы, в том числе устранение деформации и сухожильно-мышечная транспозиция с переносом функционально сохранных мышц в позицию выпавших мышц-антагонистов. Детям старше 12 лет проводили операции на костном аппарате стопы: трехсуставной артродез или корригирующие остеотомии пяточной кости, дополненные сухожильно-мышечными транспозициями.

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Результаты. Результаты лечения оценивали на основании рентгенометрических параметров и количества баллов по системе AOFAS. У всех пролеченных больных отмечено улучшение опорности стопы за счет уменьшения деформации. По шкале AOFAS среднее значение увеличилось с 42,42 до 91,14 балла.
Заключение. Учет всех причин и компонентов деформации и дифференцированный подход позволяют устранить пяточную стопу на долгосрочный период, несмотря на сохраняющиеся нарушения нейромышечной проводимости.

Ключевые слова: пяточная стопа; нейрогенные деформации стопы; сухожильно-мышечные транспозиции; трехсуставной артродез; остеотомия пяточной кости; дети.

Introduction

Calcaneal foot (*pes calcaneus*) is one of the most severe types of foot deformities and is characterized by the presence of a fixed position of foot extension without active flexion. In most cases, the development of this deformity is due to the lesion of the long flexors of the foot, primarily the gastrocnemius muscle, due to various diseases of the nervous system. According to the literature, paralytic calcaneal foot deformity develops in 5%–30% of cases of neurogenic deformities of the feet in pediatric patients [1]. It is most often detected in congenital spinal hernia, cerebral palsy, and myelodysplasia in 15%–30%, 6%, and 1% of cases [1, 2], respectively. Cases of calcaneal foot deformities due to secondary deformities are also described, for example, after treatment of clubfoot (10%) [3] and traumatic injuries of the peripheral nerves (3%) [4].

The main pathogenesis for development of this type of deformity is paralysis of the posterior group of the tibial muscles while maintaining the function of the anterior and lateral muscle groups. As a result of a decrease or complete loss of the function of the long flexors of the foot, an imbalance of forces between the flexors and extensors of the foot occurs with a sharp predominance of the latter. As a result, the foot assumes the position of extreme extension, and the calcaneal bone gradually changes from a horizontal position to a vertical position, and the calcaneal pitch increases to >30° (normal range, 25°–28°), sometimes reaching 60°–80°. The extension of the foot can reach such an extent that the dorsal surface of the foot touches the front surface of the tibia, and the calcaneotibial angle, which is normally 70°, can be reduced to 20°. Following the pathological position of the calcaneus, the osteoarticular relations between the calcaneus and talus bones change. The calcaneostragaloid angle in the sagittal plane increases by >30° (normal range, 20°–25°). When the talus bones deviate medially or laterally, the relationships in the frontal plane are also disturbed. The frontal calcaneostragaloid angle (normal range, 20°–40°) increases or decreases with the formation of calcaneal-valgus or calcaneal-varus deformity, respectively. The front part of the foot rises due to the thrust of the extensor muscles and is located above the level of the heel bone and middle section of the foot. In this regard, the angle between the talus bone and first metatarsal bone (Meary's angle) increases to 25°–30° (normal range, 0°–5°). The degree of foot deformity largely depends on the severity of neurological disorders, paralysis, or paresis of the tibial muscles.

In the literature, three forms of paralytic calcaneal foot deformity are distinguished: 1) the initial phase of deformity with a partially preserved function of the peroneal muscles; 2) pronounced deformity of the *pes calcaneus* or *pes calcaneo-valgus* with preservation of the peroneal muscles without loosening in the joint; 3) pronounced deformity with paralysis of all muscles and looseness in all joints of the foot [5]. A correlation between the parameters of excitation along the tibial and peroneal nerves and the amplitude of M-responses of muscles with the type of foot deformity was revealed [6]. Depending on the degree of muscular imbalance, calcaneal foot deformity or combined calcaneal-valgus, and less often, the calcaneal-varus deformity can develop in isolation. During walking, the support is implemented on the heel bone and partly on the middle section of the foot, depending on the degree and type of deformity. In cases of extreme deformity, only the calcaneal tuberosity is the support, where plantar callosity, ulcerations, and calluses are formed. The forefoot is not involved in the support. With age, the deformity usually progresses, the dorsum of the foot noticeably shortens, and retraction of the extensor tendons and the capsule-ligament apparatus of the dorsum of the foot occurs. When attempting a one-stage correction of the deformity, the short extensor

tendons, the retracted capsule-ligament apparatus, the deficiency of soft tissues impede bringing of the foot in the middle position.

Methods of surgical treatment of calcaneal deformity can be divided into two main categories: in young and middle-aged pediatric patients, the standard of treatment is surgery on the soft tissues of the foot, including the elimination of the deformity and tendon–muscle transpositions with transfer of functionally preserved muscles to the position of the antagonist muscles that have fallen out. At an older age, three-joint arthrodesis of the foot, osteotomy of the calcaneus, and wedge-shaped foot resections are performed to correct calcaneal foot deformity. There is an opinion that performing corrective or arthrodesis surgeries without restoring muscle balance, unfortunately, does not provide good results [7]. In this regard, methods combining corrective and arthrodesis surgery with tendon muscle transposition, namely grafting of the tendon of the long peroneal muscle and/or the posterior tibial muscle, are performed into the calcaneal canal with simultaneous shortening of the calcaneal tendon [8, 9]. However, according to a number of researchers, surgeons using such techniques are doomed to fail due to the weakness of the transplanted muscles [10]. The technique of tenodesis of the Achilles tendon to the fibula is also used for additional stabilization of the calcaneus and prevention of recurrence of the deformity [11]. The results of treatment for this type of deformity are not always stable. The reasons for unsatisfactory results and relapses are persistent muscle imbalance or its increase due to the growth of the child, as well as insufficient surgical correction [12].

Considering the above data, the results of the surgical correction of calcaneal foot deformities in pediatric patients were analyzed in our center.

Material and methods

In the Center for Pediatric Orthopedics, Priorov National Medical Research Center of Traumatology and Orthopedics, from 2008 to 2018, 13 patients with calcaneal foot deformities aged 1.5 to 15 years were treated. Both feet were deformed in eight pediatric patients; the deformity was one-sided in five patients. Surgical treatment was performed in 21 feet. The cause of the development of calcaneal deformity of the feet in eight pediatric patients was myelocele, a congenital malformation of the central nervous system. Of all patients operated during infancy; in two cases, the calcaneal deformity was secondary and developed as a result of the treatment of equino-varus deformity of the feet in the presence of myelocele; in one case, the calcaneal deformity was secondary and developed after treatment of clubfoot; one child had caudal regression syndrome accompanied by gross malformation of the caudal spine and spinal cord and a pronounced neurological deficit; in one child, calcaneal deformity of the feet was the result of genetically determined pathology, congenital structural myopathy and connective tissue dysplasia with generalized muscular hypotension, and development of the so-called "floppy infant" symptoms. Based on the type of foot deformity, we distinguished calcaneal deformity (without an element of a valgus or a varus position) in 4 feet, calcaneal foot deformity in 13 feet, and calcaneal-varus in 4 feet.

The surgical approach was determined based on the deformity rigidity, age of the child, and degree of dysfunction of the leg muscles. Contraindications for surgical correction were pronounced trophic disorders of the soft tissues in the foot and lower third of the leg. One-step surgical correction without prior use of the apparatus was performed when passive correction of extension contracture of the ankle joint to the middle position of the foot was possible without pronounced soft-tissue tension and without dyscirculatory disorders (blanching of the skin on the dorsal surface of the foot and capillary response) and without forming a rigid curved deformity of the toes due to the tension of shortened extensor tendons. In cases of rigid deformity, when there was a deficiency of skin on the dorsal surface with signs of dyscirculatory abnormalities and/or the formation of rigid curved deformity of the toes, a preliminary dosed correction was performed in the apparatus while bringing the foot in the equine position for gradual stretching of tendons and soft tissues. Pediatric patients up to 12 years, considering the functioning growth zones, underwent correction of the calcaneal foot deformity using soft-tissue release of the foot joints (11 feet). When released, capsules of the ankle, subtalar, astragaloscaphoid, and cuneonavicular joints were dissected. Due to the release of the foot, correction of the calcaneal foot deformity can be possible with the following radiometric indicators: calcaneotibial, Meary's,

and sagittal astragalocalcanean angles of 30°–50°, 20°–35°, and 30°–50°, respectively.

Pediatric patients older than 12 years underwent reconstructive osteoplastic surgeries, namely three-articular arthrodesis (7 feet) and corrective dorsal sliding osteotomy of the heel bone (3 feet). The possibility of correcting the deformity due to the sliding osteotomy of the heel bone can be possible when the radiometric calcaneotibial angle, sagittal astragalocalcanean angle, and calcaneal pitch was 20°–40°, 40°–60°, and 35°–50°, respectively. With the sliding osteotomy of the heel bone [11], the distal fragment of the heel bone with the calcaneal tuber was shifted upwards to the dorsal side so that the heel bone axis passed from the vertical position to horizontal, and the calcaneal pitch was restored to normal values.

The tendon–muscular transpositions were used when the functionality of the muscles of the tibial lateral or anterior surface corresponded to 4–5 points. The long peroneal and anterior tibial muscles were preferential for transplantation to the calcaneal tuber. With the complete loss of the tibial muscle function, tenodesis by Westin of the Achilles tendon was performed.

To assess the results of treatment, a database was compiled in Excel 10 (Microsoft, USA), followed by statistical processing using the SPSS 13.0 program. Paired Student *t*-test was used to assess accuracy. The level of statistical significance was considered at $p < 0.05$.

Results and discussion

Clinical example (Fig. 1). Patient N., 8 years old. The patient was diagnosed with myelocele and neurogenic calcaneal deformity of both feet. He complained of difficulty in walking, with the possibility of support only on both heel bones. For stability, the child curled his toes, resting on the dorsal surface of the toes phalanges, on which plantar callosity was formed. Clinically, the feet were extended at 40°, brought to the middle position with difficulty, and flexion was impossible. Muscle strength in the anterior tibial muscle to the right and left was at 5 points, peroneal muscles at 5 points, flexors of the toes at 3 points, extensors of the toes at 3 points, and the posterior group of the lower leg muscles to the right and left at 0 points. A computed tomogram of the feet shows calcaneal deformity of both feet, with the calcaneotibial angle to the right at 30°, to the left at 25°; calcaneal-supporting angle on the right at 40° and on the left at 50°. Podography revealed pathological redistribution of load with support only on the calcaneal section of both feet. Surgery was performed on the right and left feet, namely the release of the foot joints, grafting of the long peroneal muscle to the calcaneal tubercle, and lengthening of the tendon of the anterior tibial muscle. Fixing with wires with a slight hypercorrection was performed for 2 months. Splint fixation of the feet was performed after surgical hardware removal. The patient was 17 years old at 9 years after treatment. Clinically, the feet are in the middle position, and the gait is satisfactory, with support on the entire plantar surface of the feet. The patient actively performed flexion of the feet, and the amplitude of the active flexion of the left and right feet is 35° and 10°, respectively. Podography reveals significant improvement when changes in time, uniform distribution of the load on the front, and rear sections of the feet are compared. The radiograph shows the feet in the position of correction and satisfactory osteo-articular ratios; the calcaneotibial angle on the right is 70°, and on the left is 75°; calcaneal-supporting angle on the right is 25°, and on the left is 27°. When analyzing walking biomechanics based on the results of digital processing of the support reaction, an asymmetric two-humped butterfly curve was noted, and the rear push parameter was high before treatment, indicating an overload of the rear section. After treatment, a uniform distribution of the dynamic parameters of the front and rear push was noted with support on the right and left feet, and the two-humped butterfly curve became more symmetrical, corresponding to the normal two-humped curve.

When conducting radiometric measurements before and after treatment, the calcaneal pitch, calcaneotibial angle, sagittal calcaneostragaloid angle, and Meary's angle significantly improved (Table 1).

The mean value of the comprehensive assessment on the AOFAS scale after treatment was 91.14 points, which is significantly higher than that preoperatively (42.42 points).

After analysis of the obtained results, we concluded that a stable good result could be achieved after applying a differentiated approach to the treatment of neurogenic calcaneal foot

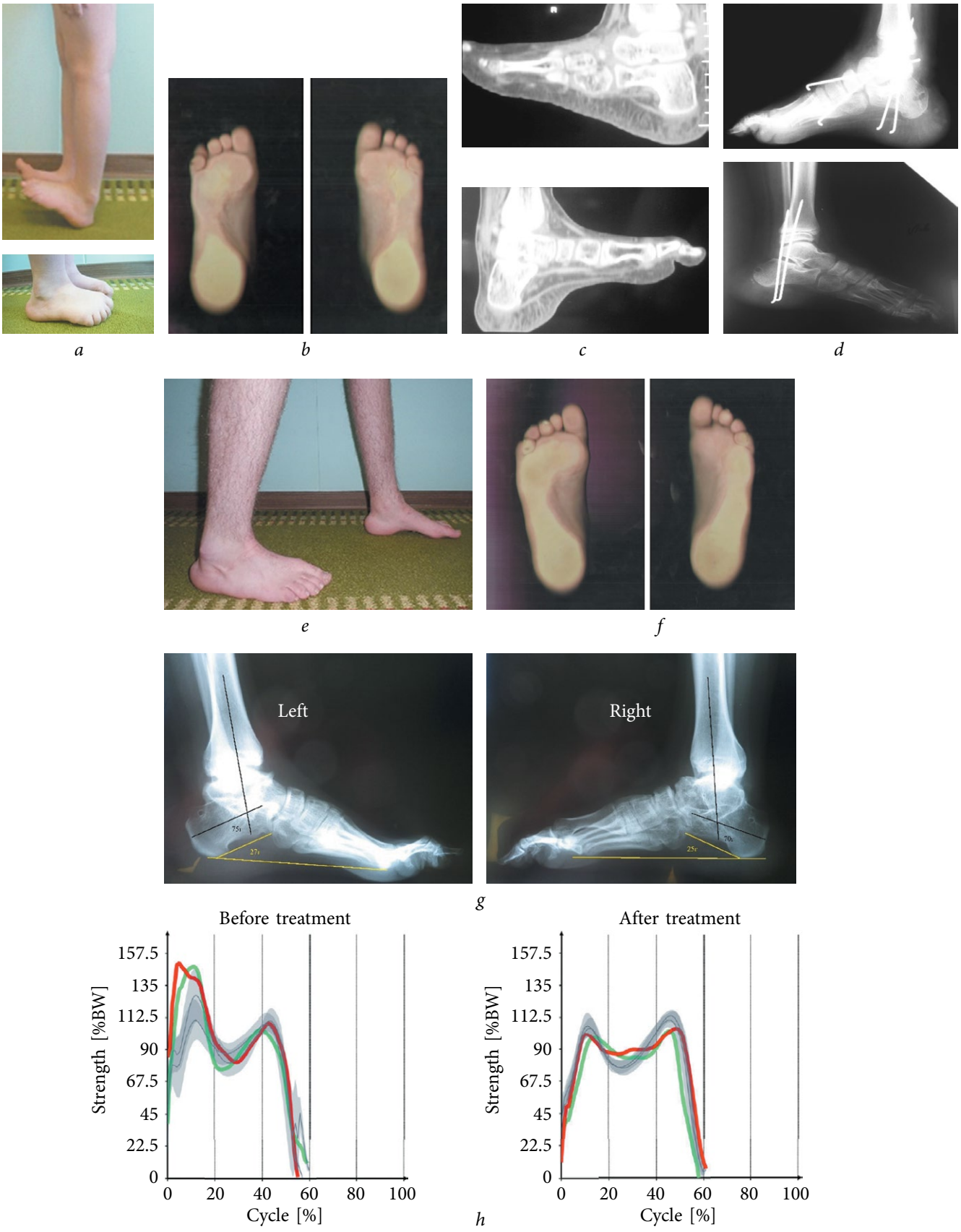


Fig. 1. Patient N., 8 years old, with a diagnosis of spinal hernia. Neurogenic calcaneal deformity of both feet: *a* — appearance of the feet under load upon admission; *b* — podography upon admission, redistribution of the load on the calcaneal section of both feet; *c* — computed tomography scans of the feet upon admission; *d* — radiographs of the feet after surgical treatment; *e* —result of treatment after 9 years, the appearance of the feet under load; *f* — podography 9 years after treatment; *g* — radiographs of the feet 9 years after treatment, the position of the correction is retained, the osteo-articular ratios are satisfactory, the calcaneotibial angle to the right is 70°, to the left is 75°; the calcaneal-supporting angle to the right is 25°, to the left is 27°; *h* — results of digital processing of the gait characteristics (support reaction) before and after treatment (red curve is right foot, green curve is left foot, gray curve is the norm corridor)

Table 1

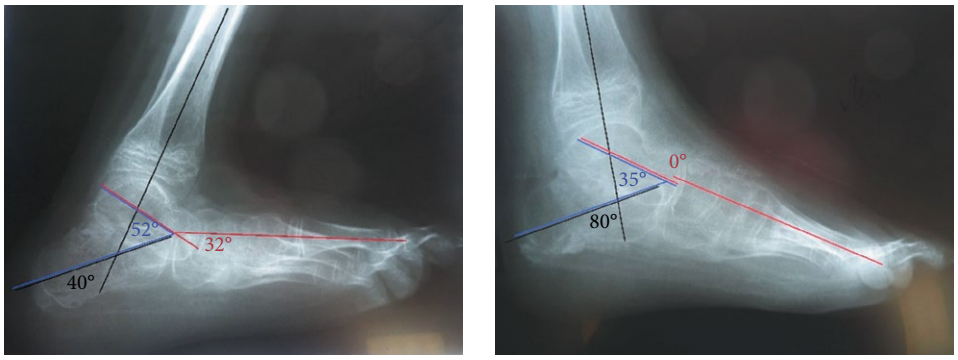
Results of radiometry before and after surgical treatment
(mean value and standard deviation)

Angle	Before the surgery	After the surgery	Accuracy index, *p*
Calcaneotibial, °	33 ± 15	72 ± 15	0.028
Calcaneal support, °	65 ± 5	26 ± 7	0.048
Sagittal calcaneostragaloid, °	48 ± 15	36 ± 5	0.026
Meary's angle, °	27 ± 17	1 ± 5	0.014

deformity. The most physiological approach to treatment can be applied in pediatric patients younger than 12 years when the correction of the deformity can be performed through intervention on the soft-tissue component of the foot with a tendon–muscular transposition. This intervention is the gold standard and enables reconstruction of the function of transplanted muscles, improving muscle balance between the flexors and extensors of the foot, which prevents relapse during the growth of the child, and also leads to the more correct development of all limb structures.

Clinical example (Fig. 2). Patient L., 11 years old. The patient was diagnosed with myelocele and neurogenic calcaneal deformity of the left foot. He complained of difficulty in walking, with support on his left heel bone. Clinically, the left foot was extended at 30°. Active foot movements are possible only with foot extension. The strength of the left tibial muscles was 5, 0, 0, 2, and 2 points in the anterior tibial muscle, peroneal (short and long) muscles, flexors and extensors of the toes, posterior tibial muscle, and a posterior group of tibial muscles, respectively. The foot was passively brought to the middle position "springy", but not maintained. Ankle flexion was impossible. Radiograph of the left foot showed calcaneal deformity, the vertical position of the calcaneus, 40° for the calcaneotibial angle, 32° for Meary's angle, and 52° for the sagittal astragalocalcanean angle. One-stage correction of the deformity was performed after considering the possible passive correction of the foot to the middle position and the child's age. The release of the foot joints (subtalar, astragaloscaphoid, calcaneocuboid, and cuneonavicular) was performed with grafting of the tendon of the anterior tibial muscle to the calcaneal tubercle; fixation of the foot with wires with slight hypercorrection (20° bending of the foot for 2 months) was performed. The foot is fixed in the splint after surgical hardware removal. Clinically, the foot is in the middle position, with support on the entire plantar surface of the foot. The X-ray image shows improvement in the osteo-articular relations in the foot, calcaneotibial angle of 80°, Meary's angle of 0°, and sagittal astragalocalcanean angle of 35°.

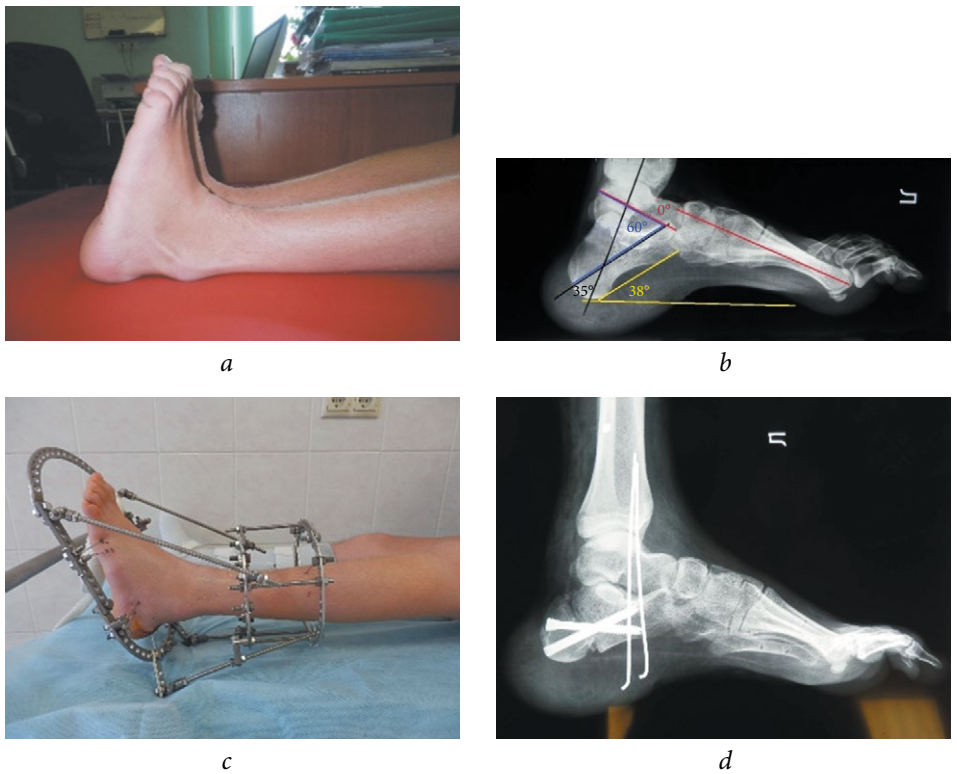
The treatment of pediatric patients older than 12 years, when the bone apparatus of the foot is already formed in the wrong position, is associated with more severe reconstructions. Three-articular arthrodesis of the foot is used in most such cases. However, its implementation without restoring muscle balance may not lead to the expected result. Calcaneal foot orientation may occur again due to the mobility of the ankle joint and the prevailing force of the foot extensors. Therefore, with a significant degree of calcaneal deformity of the foot with the prevalence of extensor muscle tone, combining three-joint arthrodesis with tendon–muscular transposition is recommended in pediatric patients of older school age. One of the infrequently used options for foot reconstruction for correction of the calcaneal deformity in adolescent patients is a complex intervention involving sliding osteotomy of the calcaneus with simultaneous tendon–muscular transposition and Achilles tendon tenodesis. At each stage of the intervention, certain tasks are solved, such as corrective osteotomy of the calcaneus with cranial displacement of the calcaneal tuber that enables elimination of the deformity, tendon–muscular transposition improves the balance between the extensor and flexor muscles of the foot; tenodesis provides prevention of recurrence of calcaneal deformity. In our opinion, this intervention is more sparing and physiological, as it allows correction of the deformity without closing the foot joints. No recurrence and satisfactory limb function were observed after a 2-year patient follow-up.



a *b*

Fig. 2. Patient L., 11 years old, with a diagnosis is neurogenic calcaneal deformity of the left foot: *a* — radiograph of the left foot in lateral projection upon admission: calcaneotibial angle is 40°, Meary's angle is 32°, sagittal astragalocalcanean angle is 52°; *b* — radiograph of the left foot in lateral projection after the surgical treatment: calcaneotibial angle is 80°, Meary's angle is 0°, sagittal astragalocalcanean angle is 35°

Clinical example (Fig. 3). Patient A., 15 years old. The patient was diagnosed with meningomyeloradiculocele of the lumbosacral spine. Neurogenic calcaneal deformity of the feet. Upon admission, the foot was extended at 25°, and flexion of the foot was impossible. During manual testing, the feet are brought to the middle position with difficulty, with a pronounced tension of the soft tissues of the dorsum of the foot, dyscirculatory disorders (tissue ischemia), and the toes are placed in a curved position due to the tension of shortened extensor tendons. Muscle strength is represented by the anterior tibial muscle on the right and left at 5 points, the fibular muscles are 3 points on the right and 1–2 points on the left, and the rear group of the lower leg muscles on the right and left are 0 point. The radiograph of the left foot upon admission shows 35° for the calcaneotibial angle, 38° for the calcaneal pitch, 60° for the sagittal astragalocalcanean angle, and 0° for Meary's angle. Considering the tension of soft tis-



a *b*

c *d*

Fig. 3. Patient A., 15 years old, with a diagnosis of meningomyeloradiculocele of the lumbosacral spine. Neurogenic calcaneal deformity of the feet: *a* — the appearance of the feet upon admission; *b* — radiograph of the left foot in lateral projection upon admission; *c* — the appearance of the foot in the first stage of treatment in the Ilizarov apparatus, flexion of the foot of 20° is achieved; *d* — radiograph of the foot in lateral projection after surgical treatment

sues, the first step in constriction of extensor tendons to reduce the risk of trophic disorders was applying the Ilizarov apparatus on the left foot and lower leg. The deformity was partially corrected in the process of distraction, and 20° flexion of the foot was achieved. At the second stage, corrective sliding osteotomy of the calcaneus was performed with fixation with Qwix screws, transposition of the tendons of the anterior tibial muscle and the short peroneal muscle, and Achilles tenodesis by Westin. On the postoperative radiograph of the left foot, calcaneal foot deformity was eliminated, with a calcaneotibial angle of 70°, calcaneal pitch of 20°, sagittal astragalocalcanean angle of 35°, and Meary's angle of 0°. Load on the foot is allowed 3 months postoperatively. Subsequently, right foot deformity was corrected based on the same scheme.

Conclusion

Based on the number of patients with calcaneal foot deformities who have applied to us for over 10 years, it can be concluded that this type of deformity is a rare pathology in pediatric patients. The primary cause for its occurrence is the lesion of the central nervous system, and, unfortunately, in these cases, regression of neurological symptoms and complete restoration of the neuromuscular apparatus of the lower extremities can hardly occur. One of the possible ways to improve the quality of life of such patients is orthopedic surgical techniques to eliminate limb deformities, which provide good support function and improve gait. The choice of the method of surgical correction should be based on the degree of the deformity rigidity, age of the patient, and parameters of dysfunction of the lower leg muscles. Considering all causes and components of the deformity in combination with a differentiated approach enables the long-term elimination of the calcaneal foot, despite the persisting disorders of neuromuscular conduction.

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Conflict of interest. The authors declare no obvious or potential conflict of interest related to the publication of this article.

Ethical review. The authors obtained the written voluntary consent of the patients (their legal representatives) to participate in the study and undergo the surgery. The study was approved by the ethical committee of the Priorov National Medical Research Center of Traumatology and Orthopedics, Protocol No. 1 dated February 8, 2019

Contribution of the authors

O.V. Kozhevnikov created the concept and design of the study and performed surgical treatment of patients, continuous and final editing of the manuscript.

S.E. Kralina created the concept and design of the study, collected and processed the material, analyzed the literature, performed surgical treatment of patients, and wrote the article.

I.V. Gribova, A.V. Ivanov collected and processed the material, performed surgical treatment of patients, questioning, and editing of the manuscript.

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