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Research Article

Role of Plantar Aponeurosis in the Formation of Cavus Component in Recurrent Congenital Talipes Equinovarus

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Abstract

Introduction: Congenital talipes equinovarus (CTEV) is the second most frequent among all congenital anomalies of the musculoskeletal system in children, and one of the most common causes of childhood disability in Ukraine. The frequency of CTEV reaches 1 - 3 cases per 1000 newborns (35 - 40% of all foot deformities). According to a number of authors, performing plantar fasciotomy can improve the shape of the foot, weight-bearing and walking functions in patients.

Aim: To determine the role of plantar aponeurosis in the formation of the cavus component in cases of recurrent CTEV in children.

Material and Methods: Mathematical research was carried out using the grapho-analytical method.

Results: In order to lower the foot arch, while correcting its cavus deformity, it is necessary to increase the length of the aponeurosis significantly (up to 25% of its initial length). To perform this task, a significant tensile force should be applied to the aponeurosis. Magnitude of force depends on the level of the foot arch lowering needed. Therefore, to reduce the height of arch by 10 mm, it is necessary to lengthen the aponeurosis by 12 mm, for which purpose a constant force of 932 N must be applied to it. To reduce the height of the foot arch by 20 mm, the magnitude of the tensile force applied to the aponeurosis must be increased to 1438 N, which is almost impossible to implement. Hence, a shortened aponeurosis is a significant obstacle for the effective elimination of cavus foot.

Conclusion:

1. Plantar aponeurosis plays a direct role in supporting the longitudinal foot arch and is one of the reasons for the persistence of cavus deformity in patients with recurrent CTEV that is not amenable to conservative treatment. To treat the cavus foot, in the absence of the effect of conservative treatment, it is necessary to lengthen it by surgical intervention (transection).
2. Correction of cavus foot requires a significant lowering of its longitudinal arch, which leads to a significant lengthening of the aponeurosis, up to 25% of its original length.
3. To ensure an increase in the length of the aponeurosis, it is necessary to have a permanently acting tensile force of a significant magnitude, exceeding 1000 N.
4. The angle of longitudinal foot arch of 110° can be chosen as a criterion for deciding in favor of preserving or cutting off the aponeurosis.

Keywords: *Congenital Talipes Equinovarus; Plantar Aponeurosis*

Introduction

Congenital talipes equinovarus (CTEV) is the second most common of all congenital anomalies of the musculoskeletal system in children and is still one of the most common causes of childhood disability in Ukraine. The frequency of CTEV reaches 1 - 3 cases per 1000 newborns (35 - 40% of all foot deformities) [1-3].

Currently, there is a large number of methods of conservative and surgical treatment of CTEV, but the presence of a significant percentage of recurrences of foot deformities in children, reaching more than 50%, necessitates a further study of this problem and improvement of diagnostic methods, pathogenetically justified treatment methods and recurrence prevention [4-9].

It should be noted that one of the typical manifestations of CTEV recurrences in children is a foot cavus, which often requires a surgical treatment [1,10-12]. Among the causal factors that form foot cavus is a shortening of soft tissue structures of the plantar foot surface (capsular ligaments of the foot, shortening of plantar aponeurosis). Plantar aponeurosis is a leading soft tissue structure that plays a role in supporting the foot arch. It starts from the calcaneal tubercle in the form of a flat strong connective tissue plate and intertwines with the plantar surface of the metatarsophalangeal joints of the foot, passing in a direction that is parallel to plantar surface of the foot, under the tendons of the long flexors of the toes, separating the superficial and deep spaces of the plantar surface of the foot. In CTEV recurrence in children, there is a shortening of the capsular ligament of the foot joints and plantar aponeurosis of the foot, which cannot always be corrected by applying stage corrective plaster casts. This is because the thickness of the plantar aponeurosis increases over time, and the elasticity decreases. According to a number of authors, performing a plantar fasciotomy can improve the shape of foot, weight-bearing and walking functions in patients [13]. However, a number of authors have doubts about the feasibility and possible negative consequences of plantar fasciotomy for the correction of the causal component of foot deformity. Therefore, the study of the role of plantar aponeurosis in the formation of the cavus component in cases of CTEV recurrence in children is also relevant.

Aim of the Study

To determine the role of plantar aponeurosis in the formation of cavus component in cases of CTEV recurrence in children.

Material and Methods

To solve the question of the influence of aponeurosis on the possibility of eliminating cavus foot in the laboratory of biomechanics of the State Institution “Sytenko Institute of Spine and Joint Pathology NAMS of Ukraine”; mathematical research were carried out using grapho-analytical method [14].

Results and Discussion

Normally, the aponeurosis performs a positive function of supporting the foot arch and ensuring its elastic deformation during weight bearing and walking. This is demonstrably shown in the diagram (Figure 1).

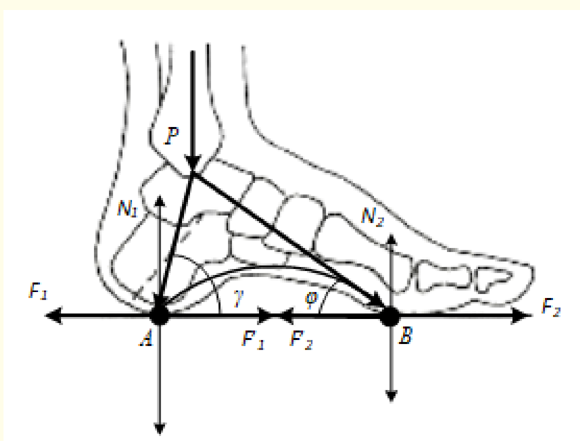

Figure 1: *Scheme of aponeurosis ensuring the elasticity of the foot arch.*

As seen in the diagram, the longitudinal foot arch is marked as *AB*, the ends of which are connected by an aponeurosis ([*AB*] segment). Body weight (*P)* acts through the shin on the ankle joint, and is divided into two components, which, through the bones of the foot, affect the weight-bearing surface at its points of contact with the heel bone (point *A*) and metatarsal bones (point B). At the points of contact with weight-bearing surface, each of the weight force components is divided into the vertical and horizontal components. The vertical components of these forces are compensated by the weight bearing reaction of N_1 and N_2. The horizontal components (F_1 and F_2) have opposite directions. They are aimed at stretching the aponeurosis. The compensation of these forces is carried out at the expense of aponeurosis reaction forces (F'_1 and F'_2), due to its elastic properties.

Calculation the total value of the tensile force acting on the aponeurosis when standing: According to literature [15,16], the anterior part of the foot normally bears 40% of body weight, the posterior - 60%. Therefore, the values of the horizontal components F_1 and F_2 can be defined as:

$$F_1 = 0{,}6P \cdot \cos\gamma$$
$$F_2 = 0{,}4P * \cos\varphi \qquad (1)$$

The total value of the tensile force acting on the aponeurosis when standing will be equal to:

$$F = 0{,}6P \cdot \cos\gamma + 0{,}4P * \cos\varphi \qquad (2)$$

or

$$F = (0{,}6\cos\gamma + 0{,}4\cos\varphi)P \qquad (3)$$

Since normally the angle of the longitudinal foot arch is 130°, the total angles γ and φ account for:

$$\gamma + \varphi = 180^\circ - 130^\circ = 50^\circ \qquad (4)$$

Next, the calculations of a tensile force value for different distribution of the total value between γ and φ angles were made, taking into account the fact that the γ angle is always greater than the φ angle:

$$\gamma > \varphi \qquad (5)$$

The results of calculations are summarized in table 1.

The magnitude of the angles, deg.		The magnitude of the tensile force relative to body weight
γ	φ	
40	10	0,85
35	15	0,88
30	20	0,90

Table 1: *The magnitude of the tensile force acting on the aponeurosis when standing, depending on the angles of weight force components on the weight-bearing surface.*

As shown by the calculations, normally when standing, the magnitude of the tensile force that acts on the aponeurosis is in the range from 85 to 90% of the magnitude of the force of body weight:

$$0{,}85P < F < 0{,}9P \qquad (6)$$

During the walking and running, the magnitude of the tensile force that acts on the aponeurosis, can increase significantly.

Thus, the aponeurosis connects the ends of the longitudinal foot arch and provides its elastic properties.

However, in the presence of congenital cavus foot, the aponeurosis is significantly reduced, as shown in the diagram (Figure 2).

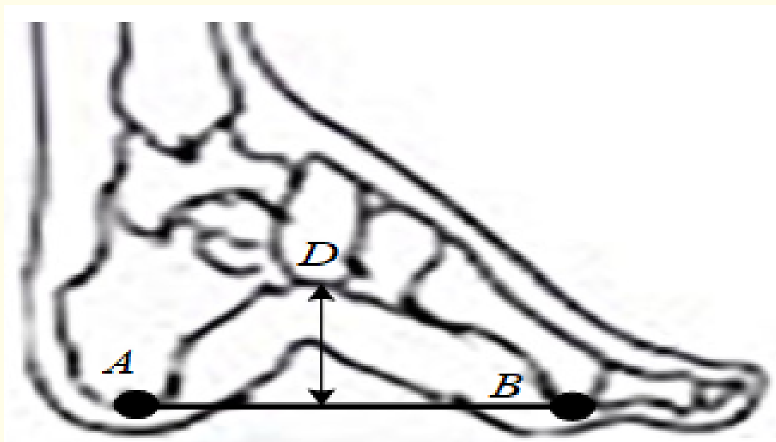

Figure 2: *Scheme of the foot with its cavus deformity.*

Since the ligament tissue is practically not stretched, the aponeurosis becomes a significant obstacle to the elimination of cavus foot, which adversely affects the results of treatment.

To determine the degree of this negative impact, a calculation scheme was developed (Figure 3).

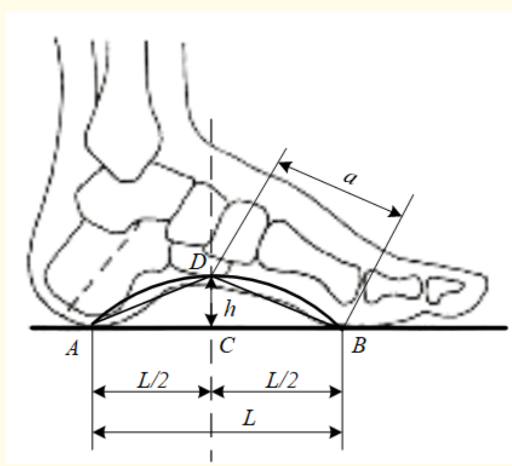

Figure 3: *Calculation scheme.*

According to the calculation scheme, the aponeurosis is represented by [AB] segment. Point C bisects this segment. Point D is the top of the foot arch, respectively, the [CD]segment is the height of the foot arch. To simplify the calculations, we approximate the ADB arc of the foot arch with two straight segments - [AD] and [BD], which will simplify the problem of determining the aponeurosis elongation required to eliminate the cavus foot - to the solution of a right triangle. To do this, the lengths of these segments are set:

[AB] = *L*;

[AC] = [BC] = *L*/2;

[AD] = [BD] = *a*;

[CD] = *h*.

Before starting the calculations, we assume that when eliminating the cavus foot, the height of its arch h decreases, but the length of the ADB arc remains unchanged. That is:

[AD] = [BD] = *a* = const (7)

Thus, it can be argued that as the height of the foot arch (h) decreases, the length of the aponeurosis L should increase.

Calculate the amount of required elongation of the aponeurosis. To do this, we should express its half-length from the BCB triangle:

$$\left(\frac{L}{2}\right)^2 = a^2 - h^2 \quad (8)$$

From equation (2), it is not difficult to determine the full length of the aponeurosis:

$$L^2 = 4(a^2 - h^2) \quad (9)$$

or

$$L = 2\sqrt{a^2 - h^2} \quad (10)$$

To determine the numerical values of the aponeurosis elongation required to eliminate the cavus foot, the initial values of the height and length of the foot arch should be set:

h = 30 mm.

a = 50 mm.

Substitute these values for equation (10) and obtain the initial value of the aponeurosis length in cases of cavus foot:

$$L = 2\sqrt{50^2 - 30^2} \quad (11)$$

or L = 40 mm.

Similarly, we obtain the value of the required aponeurosis length when reducing the height of the foot arch (h) with a step of 2 mm. The value of elongation required is determined by the formula:

$$\Lambda L = L_1 - L \quad (12)$$

Where L_1 is the length of the aponeurosis after reducing the height of the foot arch.

The results of calculations of the required aponeurosis length and its elongation are given in table 2.

The height of the foot arch (h), mm	Length of aponeurosis (L), mm	The magnitude of the aponeurosis elongation (Δ L), mm
30	40	0
28	41	3
26	43	5
24	44	8
22	45	10
20	46	12
18	47	13
16	47	15
14	48	16
12	49	17
10	49	18

***Table 2:** The values of the required aponeurosis elongation to eliminate cavus foot.*

The dependence of the elongation magnitude of the aponeurosis required on the level of the foot arch lowering to eliminate its cavus deformation is more clearly shown in the graph (Figure 4).

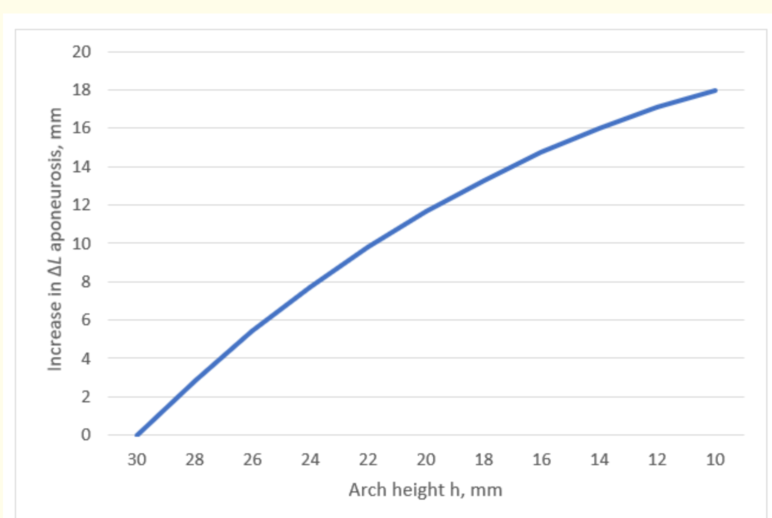

***Figure 4:** Graph of the dependence of the magnitude of the required elongation of the aponeurosis on the level of the foot arch lowering.*

As shown in the graph, to lower the foot arch by 10 mm it is necessary to extend the aponeurosis length by 12 mm; reducing the height of the arch by 20 mm requires lengthening of aponeurosis by 18 mm or almost 25% of its initial length.

Calculate the amount of tensile force that must be applied to the aponeurosis to perform the elongation needed. For this purpose, we will consider the scheme of work of an aponeurosis on stretching (Figure 5).

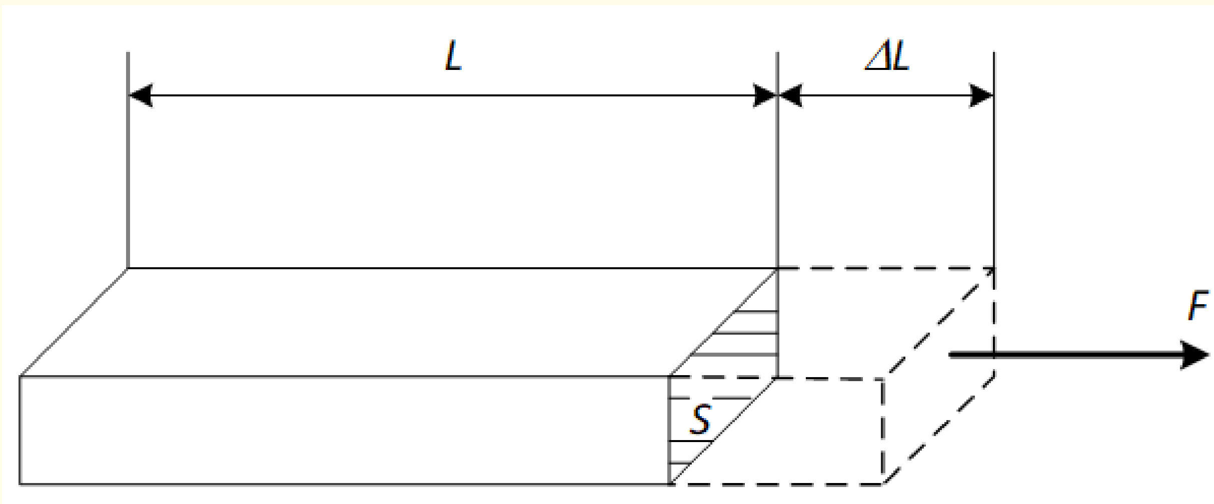

Figure 5: *Scheme of tensile aponeurosis: F – a tensile force of the aponeurosis; S - the cross-sectional area of the aponeurosis; L - the initial length of the aponeurosis; ΔL – the elongation of the aponeurosis as a result of stretching.*

Under the influence of the tensile force F, the aponeurosis changes its length L by the value of ΔL. As a result of stretching in the material of the aponeurosis there is an internal stress equal to the magnitude of the force F distributed over the area S of the cross section of the aponeurosis [2]:

$$\sigma = \frac{F}{S} \qquad (13)$$

Where *F* is the force that stretches the aponeurosis;

S is a cross-sectional area of the aponeurosis.

The relationship between the elongation of the aponeurosis and the magnitude of its internal stress is expressed by the formula [2]:

$$\sigma = E\frac{\Delta L}{L} \qquad (14)$$

Where *E* is a modulus of elasticity of the aponeurosis material;

ΔL is a magnitude of aponeurosis elongation.

Substituting the value of the internal stress of the aponeurosis material from equation (13) to formula (14) we obtain the following mathematical equation:

$$\frac{F}{S} = E\frac{\Delta L}{L} \qquad (15)$$

After performing a small transformation in formula (15), we obtain the equation to determine the magnitude of the force required to stretch the aponeurosis to any magnitude:

$$F = ES\frac{\Delta L}{L} \qquad (16)$$

To calculate the magnitude of the tensile force required to stretch the aponeurosis to eliminate the cavus foot, let's set the values of some parameters in equation (16):

E = 160 MPa [3];

S = 20 mm^2.

Substitute these data, as well as data on the initial length of the aponeurosis and its elongated, we obtain the value of the force that must be applied to the aponeurosis to lower the foot arch by a value sufficient to eliminate its cavus deformation. The results of the calculations are given in table 3.

The height of the foot arch (h), mm	The magnitude of the aponeurosis elongation (ΔL), mm	The magnitude of the tensile force (F), N
30	0	0
28	3	228
26	5	433
24	8	618
22	10	784
20	12	932
18	13	1064
16	15	1179
14	16	1280
12	17	1366
10	18	1438

Table 3: *The magnitude of the force that must be applied to the aponeurosis to lower the foot arch by a value sufficient to eliminate its cavus deformation.*

A clear idea of the amount of force that must be applied to the aponeurosis to lower the foot arch by a value sufficient to eliminate its cavus deformation, can be obtained using the graph shown in figure 6.

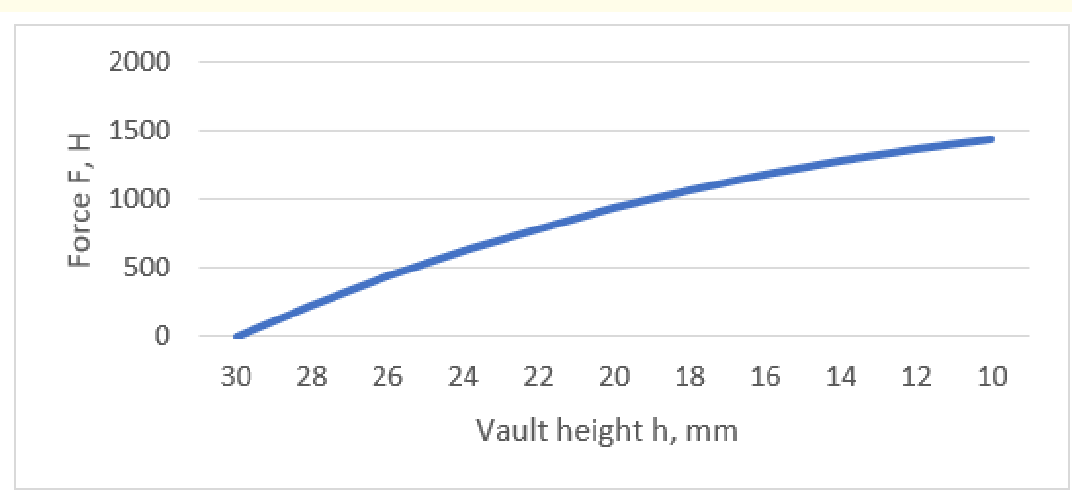

Figure 6: *Dependence of magnitude of the force to be applied to the aponeurosis on the level of the foot arch lowering, when correcting its cavus deformation.*

Studies have shown that in order to reduce the height of the foot arch, while correcting its cavus deformity, it is necessary to increase the aponeurosis length significantly (up to 25% of its initial length). To perform this task, a significant tensile force should be applied to the aponeurosis. Magnitude of force depends on the level of the foot arch lowering needed. Therefore, to reduce the arch height by 10 mm, it is necessary to lengthen the aponeurosis by 12 mm, for which purpose a constant force of 932 N must be applied to it. To reduce the height of the foot arch by 20 mm, the magnitude of the tensile force applied to the aponeurosis must be increased to 1438 N, which is almost impossible to implement.

Recall that these values are valid only for aponeurosis, the cross-sectional area of which is 20 mm^2. Since the relationship between the magnitude of the tensile force and the cross-sectional area of the aponeurosis is directly proportional (according to formula (16)), if the aponeurosis has a larger cross-sectional area, the magnitude of the force required to stretch it by a certain amount will increase directly proportional to the magnitude of the coefficient of increase in the area of its intersection:

$$K = \frac{S_1}{S} \quad (17)$$

Where S_1 is the increased value of the cross-sectional area of the aponeurosis.

The results of the calculation of the dependence of tensile force on the cross-sectional area of the aponeurosis are summarized in table 4.

The magnitude of the aponeurosis elongation (ΔL), mm	The magnitude of the tensile force (F), N			
	Cross-sectional area, mm^2			
	20	30	40	50
0	0	0	0	0
3	228	342	456	570
5	433	650	867	1083
8	618	927	1236	1545
10	784	1176	1568	1960
12	932	1398	1864	2330
13	1064	1595	2127	2659
15	1179	1769	2359	2948
16	1280	1920	2560	3200
17	1366	2049	2732	3415
18	1438	2158	2877	3596

Table 4: *Dependences of the magnitude of tensile force on the cross-sectional area of the aponeurosis.*

The dependence of the magnitude of the tensile force on the cross-sectional area of the aponeurosis could be visually compared in the figure 7.

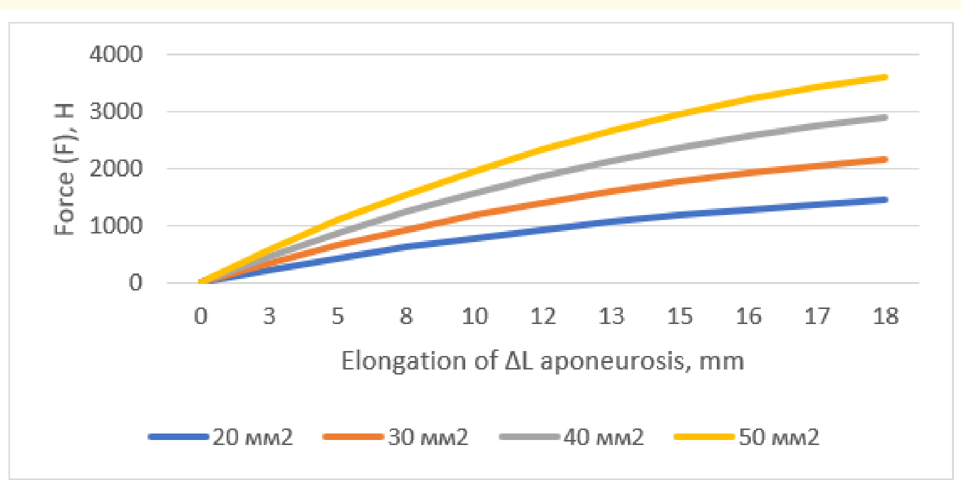

Figure 7: *Graph of the dependence of the magnitude of the tensile force on the cross-sectional area of the aponeurosis.*

As we can see in the graph, as the cross-sectional area of the aponeurosis increases, so does the amount of force required to stretch it by a certain amount. Therefore, to ensure the presence of a permanent tensile force on the aponeurosis, the value of which must exceed 1000 N, is not possible.

Therefore, the presence of a shortened aponeurosis is a significant obstacle to the effective elimination of cavus foot. The question arises in which cases the aponeurosis can be left, and in which it should be cut off. To address this issue, we choose the angle of the longitudinal foot arch as an evaluation criterion, as the angle is a value that does not depend on the size of the foot, and therefore on the sex and age of the patient. Calculate the value by which it is necessary to stretch the aponeurosis to achieve an angle of 130°, which corresponds to the normal structure of the foot.

Since, according to the calculation scheme (Figure 3), the segments [AD] and [BD] denote the bone elements of the foot, so their length remains unchanged during the correction of deformation. Therefore, the correction of the cavus foot is carried out by increasing the value of the ∠ADB angle and increasing the length of the aponeurosis (segment [AB]). We use the formula for determining the side of a triangle on the other two sides and the angle between them [4]:

$$[AB] = \sqrt{[AD]^2 + [BD]^2 - 2[AD][BD]\cos ADB} \qquad (18)$$

Where [AD] = const.

[BD] = const.

Since all patients differ from each other in the size of the feet, let us calculate the value of relative longitudinal deformation of the aponeurosis that is required for correction.

Relative longitudinal deformation is the ratio of the absolute increase in the sample length, as a result of its elastic deformation, to its initial value [2]:

$$\varepsilon = \frac{\Delta l}{l} \qquad (19)$$

Where Δl - absolute increase in the length of the sample.

l - the primary length of the sample.

The results of the calculation of the values of the relative longitudinal deformation of aponeurosis required for the correction of cavus foot at different angle values of the longitudinal foot arch are given in table 5.

Angle, Degrees	Relative longitudinal deformation, ε
90	1,28
95	1,22
100	1,18
105	1,14
110	1,10
115	1,07
120	1,05
125	1,02
130	1,00

Table 5: *The values of the relative longitudinal deformation of aponeurosis required for the correction of cavus foot at different angle values of the longitudinal foot arch.*

According to VA Berezovsky [17], the average value of the relative longitudinal deformation of human ligament is 1.13. If we take this indicator as a boundary criterion for assessing the possible self-correction of the length of aponeurosis, we can build an ostensive graph (Figure 8).

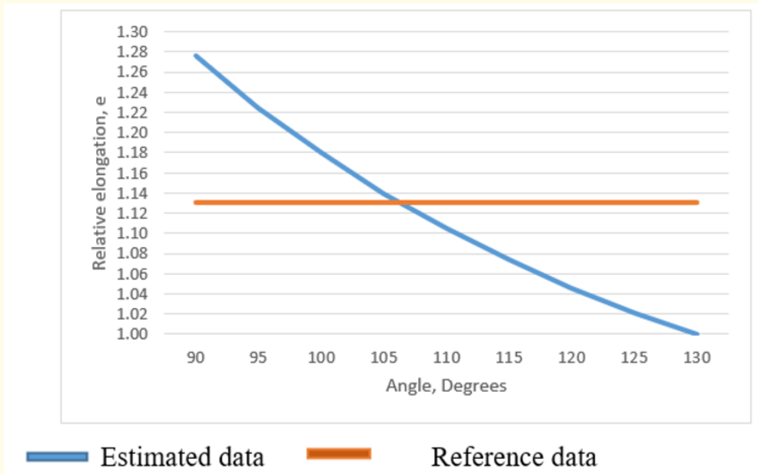

Figure 8: *Graph of the dependence of the value of the relative longitudinal deformation of the aponeurosis required for the correction of cavus foot, from the initial value of the angle of the longitudinal foot arch.*

As seen in the graph, the point of intersection of the calculated and reference data is observed between the values of the angle of the longitudinal foot arch between 105° and 110°. If we assume that the value of the relative longitudinal deformation of the aponeurosis, required to correct the cavus foot, is less than the experimental data (red line), then, over time, it is possible to correct the foot arch height to normal values, after performing other corrective manipulations, without cutting off the aponeurosis. If the indicators exceed the critical value, then the correction of the cavus foot without cutting off the aponeurosis is not possible. Thus, the angle of longitudinal foot arch of 110° can be chosen as a criterion for deciding in favor of preserving or cutting off the aponeurosis.

Conclusion

1. Plantar aponeurosis plays a direct role in supporting the longitudinal foot arch and is one of the reasons for the persistence of cavus deformity in patients with recurrent CTEV that is not amenable to conservative treatment. To treat the cavus foot, in the absence of the effect of conservative treatment, it is necessary to lengthen it by surgical intervention (transection).
2. Correction of cavus foot requires a significant lowering of its longitudinal arch, which leads to a significant lengthening of the aponeurosis, up to 25% of its original length.
3. To ensure an increase in the length of the aponeurosis, it is necessary to have a permanently acting tensile force of a significant magnitude, exceeding 1000 N.
4. The angle of longitudinal foot arch of 110° can be chosen as a criterion for deciding in favor of preserving or cutting off the aponeurosis.

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