899. The foot arch and viscoelastic properties of plantar fascia and Achilles tendon

Raminta Sakalauskaitė[1], Danguolė Satkunskienė[2]
[1, 2]Lithuanian Academy of Physical Education, Lithuania
[2]Kaunas University of Technology, Lithuania
E-mail: [1]*r.sakalauskaite@lkka.lt*, [2]*d.satkunskiene@lkka.lt*

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Abstract. Plantar fascia reduces ground reaction force on metatarsal heads. It serves to stiffen medial and lateral longitudinal arches and reduce longitudinal arch flattening. Mechanical characteristics of plantar fascia and Achilles tendon can provide significant information on fascia and tendon functional condition as well as the risks of irregularities. The objectives of this study were: (a) to identify plantar fascia and Achilles tendon oscillation frequency, decrement and stiffness, and to evaluate the reliability of differences between normal, low and high foot arch; (b) to identify the relation between plantar fascia and Achilles tendon mechanical characteristics. 42 feet of 21 soccer players were investigated in order to determine plantar fascia and Achilles tendon oscillation frequency, decrement and stiffness of feet with normal, low and high foot arch. 164 feet of 32 soldiers, 21 football players and 29 basketball players were analyzed to determine the link between plantar fascia and Achilles tendon mechanical characteristics. The medial longitudinal foot arch was evaluated according to arch index by Williams (WAI). The Achilles tendon and plantar fascia oscillation frequency, decrement and stiffness were evaluated using Myoton-3 system. This study revealed that relaxed plantar fascia of feet with normal arch is statistically reliably more elastic than fascia of feet with low arch. A very strong relationship was discovered between mechanical characteristics of plantar fascia and Achilles tendon.

Keywords: medial longitudinal arch, mechanical characteristics.

Introduction

Anatomically, the medial longitudinal arch is formed by the calcaneus, talus, navicular, three cuneiforms and the 1st, 2nd, 3rd metatarsals. In dynamic structures, the plantar fascia is essential to the maintenance of the medial longitudinal arch [1, 2]. The structural conformation of the plantar fascia in its middle part is characterized by the presence of collagen fibers reinforcing the tissue along a preferential orientation, which is supporting the major loading [3]. The plantar fascia reduces ground reaction force on metatarsal heads and reduces tensile forces in plantar ligaments, serves to stiffen medial and lateral longitudinal arches and reduce longitudinal arch flattening [4].

Low-arched foot structures and foot pronation, in particular, have been suggested to increase tensile load within the plantar fascia, thereby increasing the risk of microdamage [5, 6]. Plantar fascia inflammation and soft tissue pain are more frequent for subjects with low foot arch, since the load weighs on the whole foot and not on the heads of metatarsals. Painful calluses appear on the soft tissue areas where the load weighs heavier [7].

An elevated arch could induce greater stiffness of the feet, which would result in an inefficient capacity to dissipate foot impact forces with the ground and thus place the plantar fascia in a position of greater mechanical stress [8]. Williams et al. (2001) found that subjects with high foot arch are more likely to fracture tibia and femur, since the foot is stiff, less elastic, it does not amortize impact and the support response energy directly affects the lower limb bone.

Erdemir et al. (2004) found that plantar fascia tension and Achilles tendon tension are directly related to each other mechanically. They discovered that plantar fascia tension was directly proportional to Achilles tendon tension in cadavers in dynamic gait simulator.

Plantar fascia and Achilles tendon stresses may cause injuries, inflammation and pain in foot soft issue independently from foot arch height. The plantar fascia and Achilles tendon stresses depend on the size of the load, fascia and tendon cross-section radius and deformation extent, which is determined by tissue structure and their mechanical characteristics. Therefore, mechanical characteristics of plantar fascia and Achilles tendon can provide significant information on fascia and tendon functional condition as well as the risks of irregularities. Identification and evaluation of mechanical characteristics can be a significant measure for prevention of foot injury. Provided the plantar fascia and Achilles tendon are mechanically related foot structure parts, their mechanical characteristics must be related as well, and compensate each other in order to maintain the arch of the foot. The objectives of this study are: 1) to identify plantar fascia and Achilles tendon oscillation frequency, decrement and stiffness; to evaluate the reliability of differences between normal, low and high foot arch; 2) to identify the relation between plantar fascia and Achilles tendon mechanical characteristics.

Hypotheses:

1. Feet with normal arch will have more elastic plantar fascia and Achilles tendon than the ones with high or low arch.
2. Mechanical characteristics of plantar fascia and Achilles tendon are interrelated.

Methods

42 feet of 21 soccer players were studied in order to determine plantar fascia and Achilles tendon oscillation frequency, decrement and stiffness of feet with normal, low and high foot arch. The average age of subjects was 27.8 ± 5.1 years with an average weight of 80.1 ± 9.3 kg, and height 1.82 ± 0.1 m.

164 feet of 32 soldiers, 21 football players and 29 basketball players were analyzed to determine the link between plantar fascia and Achilles tendon mechanical characteristics. The average age of subjects was 23.9 ± 5.1 years with an average weight of 74.5 ± 11.5 kg, and height 1.77 ± 0.2 m.

All subjects who took part in this study were volunteers from a university population and the surrounding community. All subjects did not have lower-extremity abnormalities or injuries at the time of measurement. Subjects were informed about the course of the research. The National Bioethics Committee reviewed and approved the study protocol.

The medial longitudinal foot arch was measured with the digital photographic method [10] and evaluated according to arch index by Williams (WAI).

The arch index by Williams (WAI) (Fig. 1) is dorsum height (DORS) divided by arch length (AL). Dorsum height was measured from the floor to the top of the foot at 50 % of foot length. Foot length (FL) was measured from the most posterior portion of the calcaneus to the end of the longest toe. Arch length was measured from the most posterior portion of the calcaneus to the center of the first metatarsophalangeal joint. The MLA is classified as: ≥ 0,357 – high arch; 0,356–0,275 – normal and ≤ 0,274 – low MLA [11].

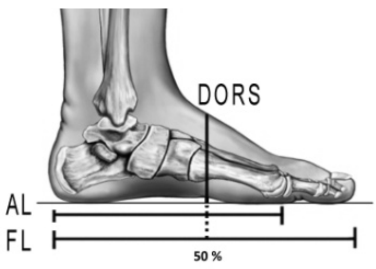

Fig. 1. The Arch Index by Williams

Fig. 2. The rearfoot angle [13]

The rearfoot (calcaneus) angle (Fig. 2) was measured as the angle between the bisection of the lower one third of the leg and the bisection of the calcaneus [12]. The MLA is classified as: normal arch 2-8°, low arch ≥ 8.1° and high arch ≤ 1.9°.

For Williams and Root research methods feet were recorded with digital video camcorder Canon XM-1 from side and back respectively. Before filming seven markers were attached to the skin in the following landmarks on the legs of each subject: 1) head of the first metatarsal, 2) dorsum midpoint between the most posterior portion of the calcaneus to the end of the longest toe, 3) most posterior portion of the calcaneus, 4) the end of the longest toe, 5) Achilles tendon origin, 6) Achilles tendon on center ankle joint and 7) third of center crural.

The fixed landmarks were manually digitized by using the software SIMI Motion. Foot length and dorsum height were analyzed from the side view. The rearfoot angle was analyzed from the back view. To verify the accuracy of the systems used, an error analysis of point appointment, repeated digitizing, and foot dorsum height and foot length appointment were conducted. The standard error of the relative mean difference was also calculated (1.1 %).

The Achilles tendon and plantar fascia oscillation frequency, decrement and stiffness were evaluated using MYOTON-3 system. The myotonometer (Fig. 3) enables us to observe mechanical oscillation of the tissue provoked by mechanical impact with an effort to avoid neurological reactions and non-elastic deformations in the tissue. The mechanical impact (0.4 N) is made by the testing-end component (with mass m = 20 g) connected to the acceleration transducer [14, 15]. The duration of the impact is set at 15 ms, after which the response of the tissue is recorded.

Fig. 3. The myotonometer [15]

The natural oscillation frequency of tissue was calculated:

$$Y = \frac{1}{T}, \tag{1}$$

where Y is oscillation frequency of the tissue (Hz), T – oscillation period in seconds.

The logaritmic decrement of oscillation damping was calculated using the ratio of the oscillation curve amplitudes (Fig. 4):

$$\Theta = \ln \frac{a_3}{a_5}, \tag{2}$$

where Θ is the oscillation logarithmic decrement of the tissue; a_3 and a_5 – the oscillation amplitudes.

The viscoelastic stiffness of the tissue was calculated:

$$C = \frac{m \times a_{\max}}{\Delta l}, \tag{3}$$

where C is stiffness of the tissue (N/m), m is the mass of the testing end, a_{max} characterizes the resistance force of the tissue and Δl is deformation depth [16, 15]. Although this device is mainly used for muscles, it is also suitable for analysis of tendon and other tissues [17].

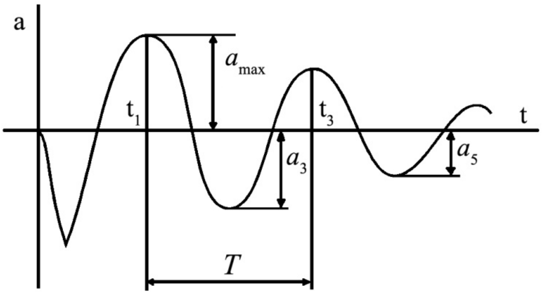

Fig. 4. The oscillation curve [17]

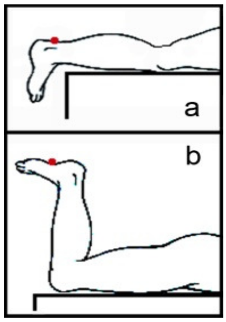

Fig. 5. The position of measurement

Relaxed Achilles tendon oscillation frequency, decrement and stiffness were measured while the subject lay on their stomach, foot in neutral position (relaxed) (Fig. 5a). Mechanical characteristics of relaxed plantar fascia were evaluated while the subject lay on their stomach with lower limb bent over knee in 90-degree angle; foot in neutral position (relaxed) (Fig. 5b). The viscoelastic properties of Achilles tendon and plantar fascia in maximum tension were measured while foot was stretched with resistance. Before the test two markers were appointed: (1) 5 cm away from the Achilles tendon attachment origin and (2) in the middle of the most posterior portion of the calcaneus and the second toe. Three measurements were taken in the same spot of the tendon to analyze their average value.

Arch index by Williams was tested for normality of distribution using SPSS 17 packet the Kolmogorov-Smirnov test.

The oscillation frequency, decrement and stiffness average and standard error for relaxed and strained Achilles tendon and plantar fascia were calculated.

The reliability of mechanical characteristics' differences was evaluated between the three types of foot arch. The reliability level chosen is 0.05.

Pearson's correlation coefficient was calculated in order to determine the link between plantar fascia and Achilles tendon mechanical characteristics.

Results

The oscillation parameters analysis of relaxed and strained plantar fascia and Achilles tendon of feet with normal, low or high foot arches.

The foot arch indexes according to Williams were distributed normally (Kolmogorov-Smirnov test: $p > 0.05$). 22 of 42 feet in this study had normal arch; their average index was 0.317 ± 0.02. There were 13 feet with low arch, for which the average index was 0.251 ± 0.02; and also 7 feet with high arch with the average index of 0.375 ± 0.01. The differences between the foot arch indexes in the three foot arch type groups are statistically significant ($p < 0.05$).

The average Achilles tendon angle of feet with normal arch was 5.16 ± 0.68 degrees, low arch – 6.78 ± 4.99 degrees, and the ones with high arch – 5.5 ± 1.2 degrees. The differences between such angles statistically are not significant.

Table 1 shows the arithmetical average of Achilles tendon and plantar fascia oscillation frequency, decrement and stiffness; and also the standard error according to foot arch type. The calculations of index reliability revealed that statistically reliable are the differences between low and normal foot arch decrement when plantar fascia was relaxed. Other indicators did not reveal reliable differences.

Table 1. The arithmetical average and standard error of Achilles tendon and plantar fascia oscillation frequency, decrement and stiffness

Mechanical characteristic / Arch		Low	Normal	High
Relaxed Achilles tendon	Frequency, Hz	33.45 ± 3.05 #	32.59 ± 2.91 #	32.14 ± 1.72 #
	Decrement	0.95 ± 0.23 #	0.97 ± 0.15 #	1 ± 0.10 #
	Stiffness, N/m	692.3 ± 57.44 #	676.59 ± 44.41 #	685 ± 22.32 #
Strained Achilles tendon	Frequency, Hz	56.26 ± 16.09	51.48 ± 20.17	59.72 ± 3.31
	Decrement	1.41 ± 0.48	1.37 ± 0.62	1.51 ± 0.63
	Stiffness, N/m	1150.84 ± 73.34	1130.59 ± 142.99	1168.71 ± 119.72
Relaxed plantar fascia	Frequency, Hz	26 ± 3.47 #	25.01 ± 3.09 #	25.1 ± 2.05 #
	Decrement	1.81 ± 0.15 * #	1.65 ± 0.16 * #	1.74 ± 0.12 #
	Stiffness, N/m	457.15 ± 48.40 #	446.4 ± 46.17 #	445.28 ± 35.47 #
Strained plantar fascia	Frequency, Hz	40.07 ± 5.60	40.76 ± 7.45	41.01 ± 3.65
	Decrement	1.11 ± 0.33	1.1 ± 0.26	1.05 ± 0.31
	Stiffness, N/m	753.3 ± 78.17	737.18 ± 120.38	767 ± 57.16

Note. * Statistically significant difference between foot arch types ($p < 0.05$).
Statistically significant difference between relaxed and strained condition ($p < 0.05$).

The comparison of frequency, decrement and stiffness arithmetical average between relaxed and strained tissue condition allowed us to discover that all Achilles tendon and plantar fascia parameters of feet with low, normal and high arch had statistically significant differences ($p < 0.05$).

Analysis of interaction between plantar fascia and Achilles tendon mechanical characteristics.

According to Williams, foot arch indexes of 164 students were distributed normally (Kolmogorov-Smirnov test: $p > 0.05$). 83 of 164 feet had normal arch; their average index was 0.324 ± 0.02. 14 feet had low arch with the average index of 0.253 ± 0.02 and 67 feet had high arch, which average index was 0.389 ± 0.03. The differences between foot arch indexes of three foot arch types are statistically significant ($p < 0.05$).

The Achilles tendon average angle of feet with normal arch was 5.9 ± 3.6 degrees, of feet with low arch – 6.5 ± 2.5 degrees, and the average Achilles tendon angle of feet with high arch was 4.5 ± 3.5 degrees. Statistically significant differences are the ones between feet with normal and high arch ($p < 0.05$), whereas the differences between other angles are statistically unreliable.

The interaction of Achilles tendon and plantar fascia mechanical characteristics is represented in Fig. 6. A significant positive relation was discovered between oscillation frequency of plantar fascia and Achilles tendon. Higher frequency in fascia means higher frequency in Achilles tendon as well. A strong positive relation was also discovered between plantar fascia and Achilles tendon decrement. The higher the decrement was, the lower was elasticity of the tissue. This means that along with lower fascia tension the tendon tension decreases as well. A very strong relation was also established between plantar fascia and Achilles tendon stiffness. As fascia stiffens, the tendon stiffens too. A strong reverse relation was detected between plantar fascia oscillation frequency and Achilles tendon stiffness. These results reveal that plantar fascia is more elastic when Achilles tendon is stiffer.

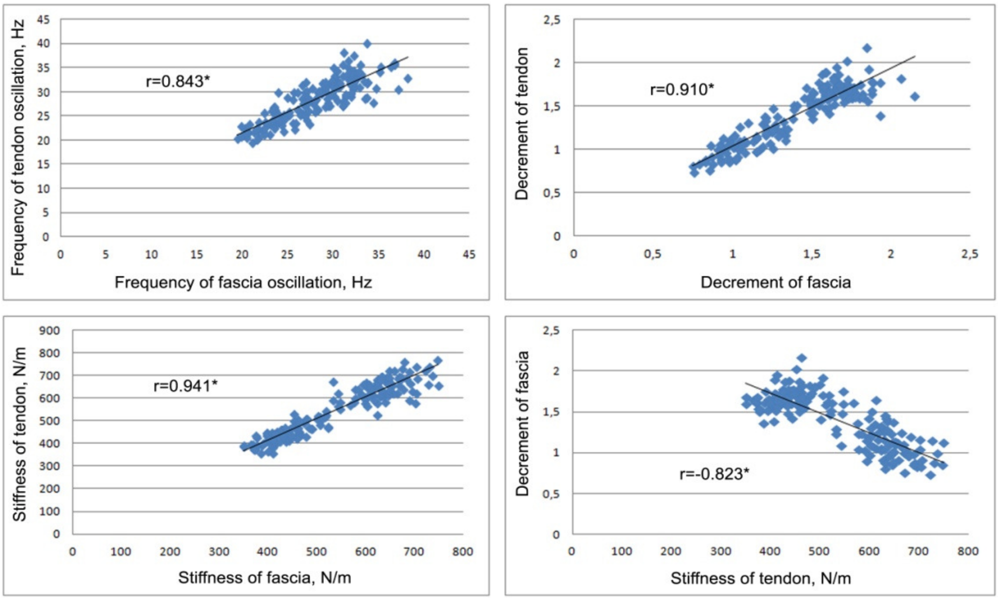

Fig. 6. The correlation link between mechanical properties of plantar fascia and Achilles tendon
Note. * Correlation is significant at the 0.01 level.

Discussion

One of the goals in this study is to determine Achilles tendon and plantar fascia oscillation frequency, decrement and stiffness in different conditions (while foot is relaxed and strained), and also to evaluate the reliability of differences between feet with normal, low and high arch. The research showed that a relaxed foot with normal arch is reliably more elastic than the one with low arch (oscillation decrement was 9.70 % lower respectively). Sahin et al. (2010) claims that plantar fascia elasticity is reduced when the arch is excessively high or low, thus increases the load on plantar fascia. High value of low and high foot arch decrement found during our research indicates that plantar fascia of such feet was less elastic than the fascia of feet with normal arch. Although there were no reliable differences between high and normal arch fascia decrement, there were also no statistically reliable differences between decrement of feet with low and high arch. Therefore we can conclude that our results correspond with Sahin‘s statement.

Variations between relaxed and strained plantar fascia show changes in mechanical characteristics of feet with normal, high and low arch during stretching. We consider these deformations to be significant since the changes of plantar fascia oscillation frequency, stiffness and decrement that occurred during the change of state were statistically reliable ($p < 0.05$). During the deformation of plantar fascia the oscillation frequency of low and high arch feet decreased by 40 % and feet with normal arch – by 35 %. The reduction of decrement during stretching plantar fascia demonstrates it‘s increasing elasticity.

Relaxed fascia of the feet with normal arch were more elastic than the ones with low or high arch. Meanwhile, during the process of stretching feet with low and high arch, increased elasticity in comparison with normal arch feet was observed. However, the final elasticity was equal when reached ultimate stretching point regardless of arch height. Why fascia of the feet with normal arch did have highest elasticity rates? If the more strained fascia is, the more elastic it is, then we can assume that feet with low and high arch have less intense stress while relaxed than the ones with normal arch. Provided the load is steady, the stress of a tissue depends on its cross-section radius. Wearing et al. (2007) found that thickness of healthy feet fascia does not depend on the height of the foot arch; however, when heel pain is present, thickness of plantar fascia was discovered to be greater of those feet with low arch ($r = 0.89$, $p < 0.05$). It is yet not clear how plantar fascia thickness is related to fascia inflammation (heel pain): weather greater fascia thickness shows it‘s adaptation to greater stress and pain, or maybe by nature thicker fascia cannot adapt to heavier load on feet causing heel pain [19]. It was discovered that physical activity has impact on the thickness of plantar fascia distal part, whereas thickness of fascia proximal part does not depend on physical activity [20]. It is also known that thickness of plantar fascia does depend on subjects’ gender and body mass [21]. A medium strong positive correlative relation was found between subjects’ height, body mass and plantar fascia thickness ($p < 0.05$) [20]. All subjects in this research were healthy, young, physically active whose height in various age groups was not significantly different; they experienced no pain in plantar fascia. In this research we discovered a statistically significant difference between body mass and body mass index of subjects’ with low and high foot arch: subjects with low foot arch also had low body mass and low value of body mass index. This leads to a conclusion that increased elasticity of plantar fascia with normal foot arch (which grows while stretching fascia) is more related to its morphological features which determine mechanical tissue characteristics than fascia thickness. Tissue characteristics depend on the constituent material properties and their interaction: water and solids ratio, the structure, size, dispersion direction of collagen fibers and their relation with intercellular filler [22]. Plantar fascia is a dense connective tissue which microscopic structure is similar to foot ligaments [23]. There are a great number of densely located collagen fibers in fascia which ensure tissue elasticity. The dominant fascia cells are fibroblasts; although some researchers claim that as a result of mechanical load α smooth muscle actin might increase which leads to an increased number of myofibroblasts in the tissue [24]. Benjamin and Raplhs (1998), Kumai and Benjamin (2003) state that fibroblast modulation into fibrochondrocytes cause solid tissue adaptation to pressure (compressing load). Other scientists claim fascia to be the linking tissue where adipose tissue interlace with fiber [27]. Such fascia histological variety and shift suggests that due to structural fascia peculiarities the mechanical characteristics of fascia with different foot arch can differ significantly, and such peculiarities partly depend on the size, duration and nature of mechanical load. We have come to a conclusion that the nature of mechanical load inflicted on fascia depends on the size of foot arch. Heavy load on fascia with normal and high arch makes metatarsals slide forward and arch plunges down; however, the foot does not press on support with full sole surface. In such case plantar fascia is being stretched. Feet with low arch press on support with full surface, therefore such fascia are not only being stretched but also compressed. Foot arch size impact on the load structure on plantar fascia and its modulation have not been analyzed yet, therefore discussions about foot arch impact on fascia elasticity and its interaction with load structure can only be hypothetical.

Foot arch height is associated with foot pronation degree, which is reflected by Achilles tendon angle. Our research indicates that Achilles tendon angle of the feet with low arch was reliably greater than the ones with high arch thus confirming that pronation of feet with low arch is significantly greater. This suggests that foot pronation increases the load on Achilles tendon. Its stresses are more intense because calcaneus rotation causes tendon’s length increase. Plantar fascia fibers pass to calcaneus protuberance splint. Achilles tendon fibers attach themselves to the back side of calcaneus protuberance [28].

The height of foot arch is related to foot pronation degree, which is reflected by Achilles tendon angle. Our research showed that Achilles tendon angle of feet with low arch was reliably greater than the ones with high foot arch. These results confirm that low arch feet pronation is significantly greater. This suggests that foot pronation increases load on Achilles tendon. The stresses are greater since calcaneus rotation causes tendon's length increase.

Plantar fascia fibers pass to calcaneus protuberance splint. Achilles tendon fibers attach themselves to the back side of calcaneus protuberance [28]. It was determined that while stretching fingers plantar fascia stretches as well and increases tension in Achilles tendon [29]. Furthermore, plantar fascia stresses strongly correlate (r = 0.76) with Achilles tendon tensile force [9]. Such anatomical and functional similarities between plantar fascia and Achilles tendon confirm and clarify our research results, which indicate strong correlative relation between mechanical characteristics of plantar fascia and Achilles tendon.

Conclusions

1) The study of plantar fascia and Achilles tendon mechanical characteristics revealed that relaxed plantar fascia of feet with normal arch is statistically reliably more elastic than fascia of feet with low arch. There was no reliable difference between relaxed feet decrement of feet with normal and high arch and also no reliable difference between feet with high or low arch.

2) A very strong (0.84–0.94) correlation was discovered between mechanical characteristics of plantar fascia and Achilles tendon. Stiffer and more elastic fascia implies analogous properties in tendon. A strong reverse correlation (–0.82) was observed between Achilles tendon stiffness and plantar fascia elasticity: the stiffer the tendon, the more elastic is fascia.

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