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THEORETICAL AND EXPERIMENTAL STUDY ON DURABILITY OF THE CALCANEAL TENDON AND THE PATHOMECHANISM OF ITS ATRAUMATIC, SUBCUTANEOUS BREAK

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ABSTRACT: The pathology of the calcaneal tendon (Achilles) presents a serious medical and social problem. This tendon is the strongest plantar flexor of the foot that plays a fundamental role in the accomplishment of human gait. Although this role has long been recognized, neither in medical nor in biomechanical literature can one find a clear description of subcutaneous break of the Achilles tendon. Its pathomechanism and the causes have not been fully accounted for. Many authors concentrate mainly on medical and biological aspects of the damage of the Achilles tendon.They often claim that the vasculature of the tendon itself plays a significant role in the pathogenesis, because the blood supply to the tendon changes with human age, decreasing substantially after the age of 30, leading both to regressive changes in the tendon as well as to a reduction of the tendon's mechanical strength. The refore a comprehensive description and explanation of this phenomenon needs an interdisciplinary approach, taking into account not only the medical and biological aspects, but also the mechanics sensu largo. The aim of the paper is to put forward a complete description of the pathomechanism of the Achilles tendon spontaneous break, within the framework of its mechanics. The conclusions are based upon a kinematical analysis of the knee joint, a trajectory determination of the point of origin of the gastrocnemius from the initial position of 90 degrees bent up to the full knee extension, and an experimental examination of uniaxial stretching of the Achilles tendon.

KEY WORDS: biomechanics, kinematics, pathomechanism, investigations

INTRODUCTION

The literature on the pathomechanism of spontaneous Achilles tendon break describes different essential factors helpful for an analysis of work mechanics of the muscular and bone systems of the human lower extremity during generation of movement, i.e. walking, running, jumping [2-5,7].The pathomechanism is usually explained in terms of its mechanics when a sudden, uncoordinated spasm of the triceps surae (particularly with the foot bent plantarly and the leg extended) may lead to breaking it. This general theory cannot be accepted because it does not take into consideration the cause-result phenomena, without which the descriptions of such an injury are too enigmatic and do not comprise the whole complexity of the issue. It also lacks the mathematical basis in the description of the physical phenomena contributing to the subcutaneous break of the calcaneal tendon. In order to expand the knowledge and provide a better explanation as well as to describe this phenomena it was crucial to conduct interdisciplinary research considering both the medical and biological aspects as well as the mechanics in broad sense of the word.

In order to obtain the additional information required it was necessary to conduct a static uniaxial tensile trial of the calcaneal tendon to determine its durability, consider the mechanics of the muscles involved in the movement of the extremity and the forces generated, conduct a kinematical analysis of the knee joint to calculate the trajectory of the point of origin of the biarticular muscle of the calf. Describe the geometrical dimensions of the tendon, perform analytical calculations. Consequently, with the results being as they are, use them to define the phenomenon of the non-traumatic, subcutaneous break of the calcaneal (Achilles) tendon.

Aim of the paper

The aim of this paper is a complete description of the pathomechanism of the non-traumatic subcutaneous break of the calcaneal tendon, of the human lower extremity, using:

1) The results of the conducted static uniaxial tensile trial of the calcaneal (Achilles) tendon to determine its durability.
2) A kinematical analysis of the knee joint with a mathematical model in order to determine the coordinates of the points on the movement trajectory, the point of origin of the medial head of the gastrocnemius muscle, from the flexion of the femur to its full extension.

3) Calculating the path length of the point of origin of the medial head of the gastrocnemius muscle, during the full extension of the extremity.

4) Considering the mechanics of muscles involved in the movement of the extremity and determine the values of forces generated by them while lifting humans own body mass.

MATERIALS AND METHODS

Natural Achilles tendons acquired from fresh human corpses averagely 12 hours after death have been used for the static uniaxial tensile trial. So as to mount them properly in the grip of the tensile trial machine, they have been taken along with a fragment of calcaneal bone tuber. Whereas, in the proximal section, at the level of transition into the gastrocnemius muscle, they have been separated form other muscular structures. In order to conduct comparative study, the tendons have been sampled from both left and right lower extremities. The calcaneal bone, like all other tarsal bones is made only of the spongy bone, which consists of the bone lamellae which form the trabeculae. Their shape and size depend on the direction of the forces affecting the bone. After trimming its spongy, susceptible to pressure structure was revealed. When subjected to any force normal to the cut surface, it easily suffers destruction. Therefore in such form it could not be used as a mounting surface. Yet, when untrimmed it makes relatively strong anatomical element of the foot. In order to reinforce the bony structure, a procedure of vacuum suction of the bone marrow from this fragment was performed, and then specially prepared epoxy resin was introduced into the spongy-porous part. Before the tensile trial each tendon had been described (length, circumference in loco typico, as well as height and width of the calcaneal tuber). Moreover, a metric containing the following data: autopsy number, date of death, sex, individual's age and the extremity tat had been sampled had been filled out.

Tensile trial

The trials have been conducted using INSTRON 1126 tensile trial machine, MTS MINI BIONIX 8502 system machine and special grips to mount the Achilles' tendons. Also the appropriate measuring sensors-extensometers have been used for measuring the longitudinal extension.

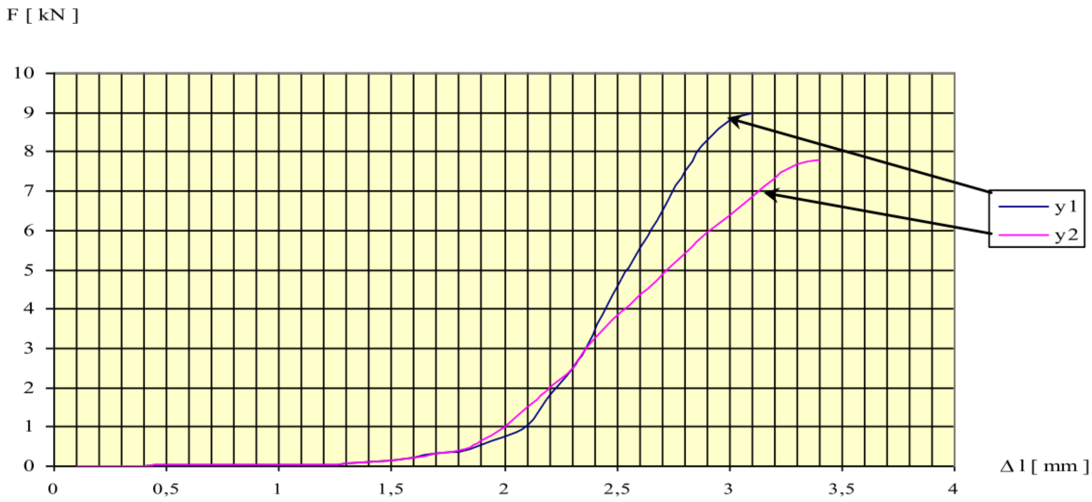

FIG. 1. CURVES FROM TENSION OF THE ACHILLES TENDON OF LEFT (y1) AND RIGHT (y2) LOWER EXTREMITY OF A MALE INDIVIDUAL AGED 20 IN DEPENDENCE F (ΔL)

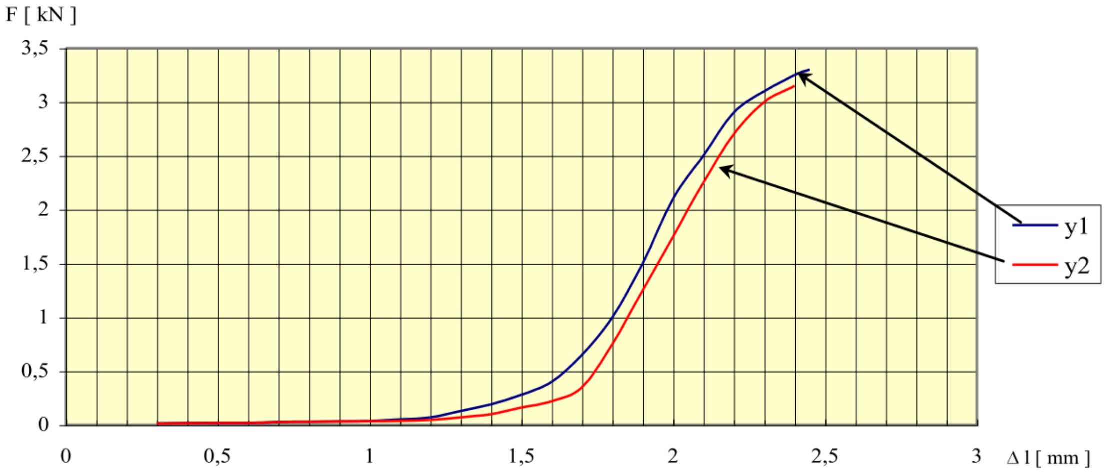

FIG. 2. CURVES FROM TENSION OF THE ACHILLES TENDON OF LEFT (y1) AND RIGHT (y2) LOWER EXTREMITY OF A MALE INDIVIDUAL AGED 78 I N DEPENDENCE F (ΔL)

RESULTS

Dependency graphs F (Δl) for the tendons of both extremities of a male individual age 20 are shown on Figure 1, while form a male aged 78 on Figure 2.

It has been observed that in the right-handed males the left Achilles tendon tends to be much stronger than the right one (for the same individual [6]). Comparison of mean values of the forces stretching the tendon of the human lower right extremity F (t) and value of the forces stretching the tendon of the human lower left extremity, depending on age, for 65 pairs of tested tendons, is shown on Figure 3.

While analyzing the results in the form of a function graph F (t) (fig.3) it can be noticed that the durability of the calcaneal tendon of the right and left extremity, described in the form of a curve, asymptotically converge along with the human age, reaching the level of 1/3 of their initial durability. While the relative longitudinal extension is contained between 3.06% and 4.37% for the tendons of the lower right extremity (Table 1), yet between 3.06% and 3.87% for the tendons of the lower left extremity (Table 2)

From the analysis of the gathered data and the curves presented on the graph it can be concluded that quasi-linear interrelation between the load and longitudinal extension results mainly from the regular-ordered structure of the tendon. In the strength range dependent on the mass of the individual, the tendon behaves like a viscoelastic body.

Kinetic analysis

In order to determine the coordinates of the motion trajectory points of the origin point of the medial head of the gastrocnemius muscle, from the flexion of the femoral bone to its full extension, the kinetic analysis of a knee joint has been described using the mathematical apparatus in the research [10], in which the path length of the origin point of the gastrocnemius has been calculated.

While considering the pathomechanism of spontaneous break of calcaneal tendon, it is necessary to describe the motion trajectory, and subsequently to calculate the path of the origin point of the medial head of the gastrocnemius just superior to the medial condyle of the femur, marked with the letter “M”, because of the position of the flexed thigh in relation to the shin, until full extension of the knee joint.

The trajectory (Fig. 4) has been described with a degree 9 polynomial, which has the following coefficient values:

a_0=45,37775 a_1=0,038235
a_2=0,157479 a_3=-0,03727
a_4=0,003823 a_5=-0,00021
a_6=7E-06 a_7=-1,3 E-07
a_8=1,36E-09 a_9=-5,8E-12

TABLE 1. FOUR EXAMPLES CHOSEN OUT OF THE MEASUREMENTS ACQUIRED DURING THE STATIC TENSILE TEST OF 65 ACHILLES TENDONS FROM HUMAN RIGHT LOWER EXTREMITIES [1,6,9-11]

No.	Age [years]	Sex	Sample length [mm]	Stretching force [kN]	Longitudinal extension *Δl* [mm]
1	20	M	80	7.8	3.4 (4.25%)
2	30	M	80	4.7	3.5 (4.37%)
3	60	M	80	3.7	2.55 (3.18%)
4	78	M	80	2.9	2.45 (3.06%)

TABLE 2. FOUR EXAMPLES CHOSEN OUT OF THE MEASUREMENTS ACQUIRED DURING THE STATIC TENSILE TEST OF 65 ACHILLES TENDONS FROM HUMAN LEFT LOWER EXTREMITIES [1,6,9-11]

No.	Age [years]	Sex	Sample length [mm]	Stretching force [kN]	Longitudinal extension *Δl* [mm]
1	20	M	80	9	3.1 (3.87 %)
2	30	M	80	7	3.0 (3.75%)
3	60	M	80	4	2.55 (3.18%)
4	80	M	80	3.3	2.45 (3.06%)

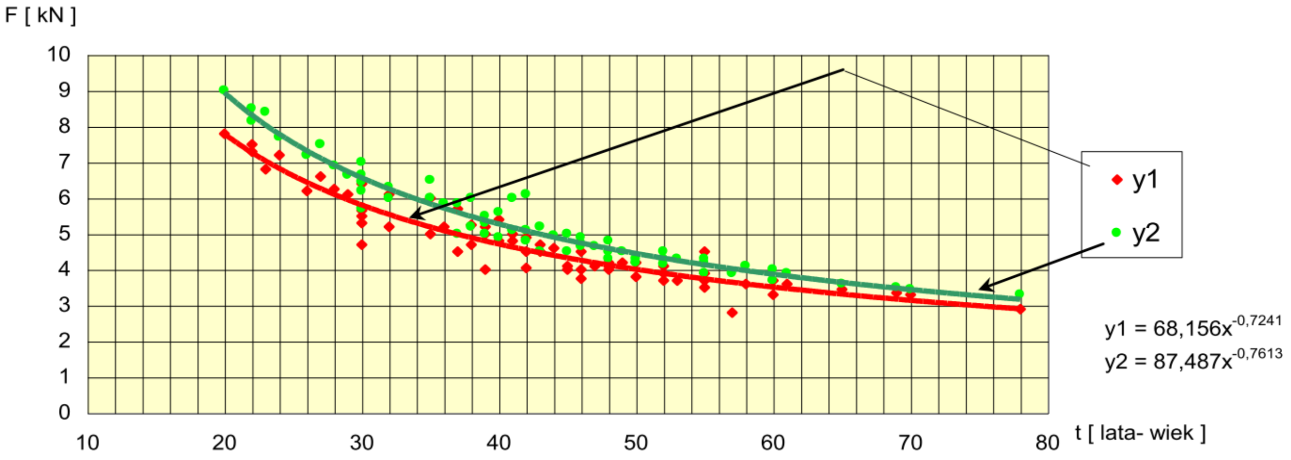

FIG. 3. COMPARISON OF THE VALUE OF THE FORCE STRETCHING THE ACHILLES TENDON OF THE LOWER LEFT HUMAN EXTREMITY (y2) IN RELATION TO THE VALUE OF THE FORCE STRETCHING THE TENDON OF THE LOWER RIGHT EXTREMITY (y1), DEPENDING ON THE INDIVIDUAL AGE

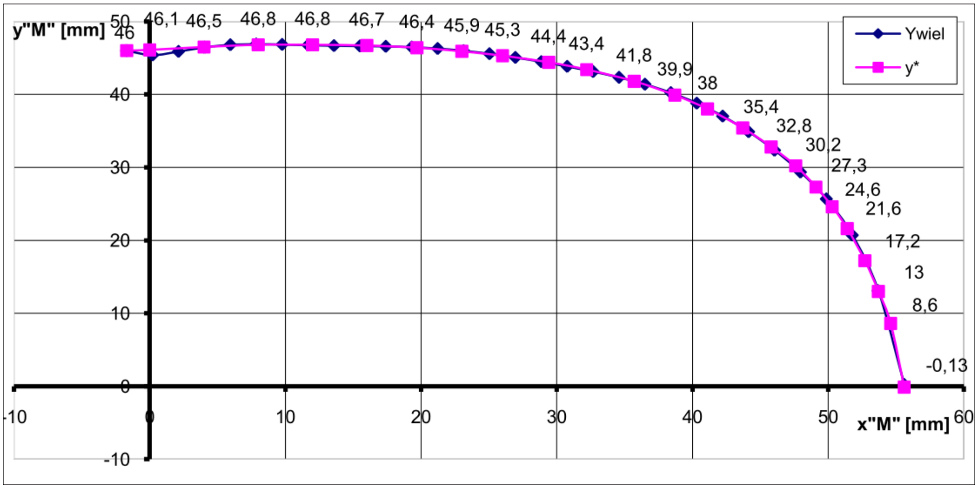

FIG. 4. TRAJECTORY OF THE POINT "M" OF THE ORIGIN OF THE MEDIAL HEAD OF THE GASTROCNEMIUS ON THE FEMORAL BONE FOR THE EXTENSION OF THE KNEE JOINT

TABLE 3. COORDINATES OF THE POINTS ON THE TRAJECTORY AND PATH LENGTH OF THE ORIGIN POINT "M" OF THE MEDIAL HEAD OF THE GASTROCNEMIUS FROM FLEXION TO THE FULL EXTENSION OF THE KNEE JOINT

Point no.	x	y	Length increase	Distance form p3 [mm]	Distance from p4 [mm]
2.0	55.60	-0.13			
3.0	54.60	8.60	0.00	0.00	-16.59
3.1	53.70	13.00	4.49	4.49	-12.10
3.2	52.70	17.20	4.32	8.81	-7.78
3.3	51.40	21.60	4.59	13.40	-3.20
4	50.30	24.60	3.20	16.59	0.00
4.1	49.10	27.30	2.95	19.55	2.95
4.2	47.60	30.20	3.26	22.81	6.22
4.3	45.80	32.80	3.16	25.97	9.38
5.0	43.70	35.40	3.34	29.32	12.72
5.1	41.10	38.00	3.68	32.99	16.40
5.2	38.70	39.90	3.06	36.05	19.46
5.3	35.70	41.80	3.55	39.60	23.01
6.0	32.20	43.40	3.85	43.45	26.86
6.1	29.40	44.40	2.97	46.43	29.83
6.2	26.00	45.30	3.52	49.94	33.35
6.3	23.00	45.90	3.06	53.00	36.41
7.0	19.70	46.40	3.34	56.34	39.75
7.1	16.00	46.70	3.71	60.05	43.46
7.2	12.00	46.80	4.00	64.05	47.46
7.3	8.00	46.80	4.00	68.05	51.46
7.4	4.00	46.50	4.01	72.07	55.47
7.5	0.00	46.10	4.02	76.09	59.49
8.0	1.70	46.00	1.70	77.79	61.20

The results presented in Table III, are followed by the conclusion, that the calculated maximum path length of the point "M"-origin of the medial head of the gastrocnemius is 77,79 mm, but it should be remembered that this is not the actual path. It has been calculated for a system in which certain simplification had been adopted, i. e. the flatness of the superior articulation surface of the medial condyle of the tibia. Despite that, the information gathered in this form and with such accuracy, permits more precise approach to the description of the knee joint mechanics.

Considering the mechanics of the muscles involved in limb movement, values of the forces generated by them while starting the motion of lifting individual's own body mass have been determined.

While investigating the equilibrium of the forces in the presence of static load on the knee joint, one can compute their values out of the equilibrium conditions:

Force F_f of the quadriceps femoris muscle, has been described with the following dependence:

$$F_f = \frac{F_q - \sin \alpha_q + Q_m - F_q \cdot \cos_q \cdot tg\,\alpha_p}{\cos \alpha_f \cdot tg\,\alpha_p - \sin \alpha_f}$$

Where: F_p-Force of interaction between tibia and femoral condyle

Q_m-body mass

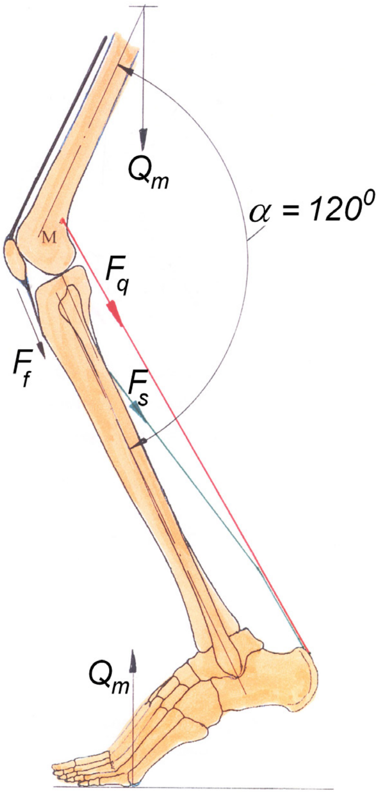

FIG. 5. PICTURE OF THE FORCES IN THE MUSCLES OF THE LOWER EXTREMITY INITIATING THE MOTION OF LIFTING THE BODY MASS

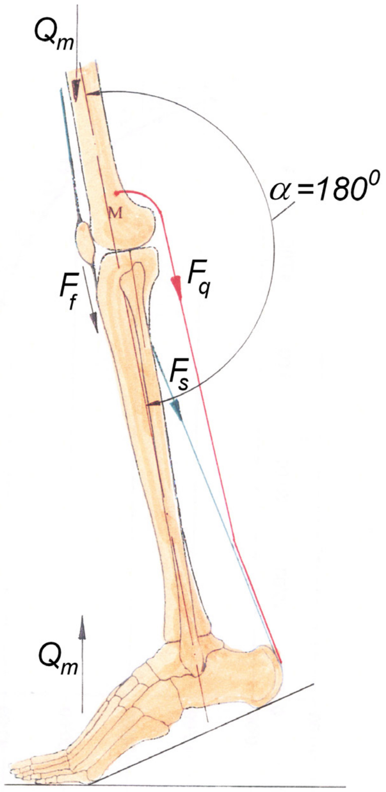

FIG. 6. ROTATION OF THE FEMORAL BONE IN THE KNEE JOINT AND THE MOVEMENT OF THE POINT "M" OF THE ORIGIN OF THE GASTROCNEMIUS

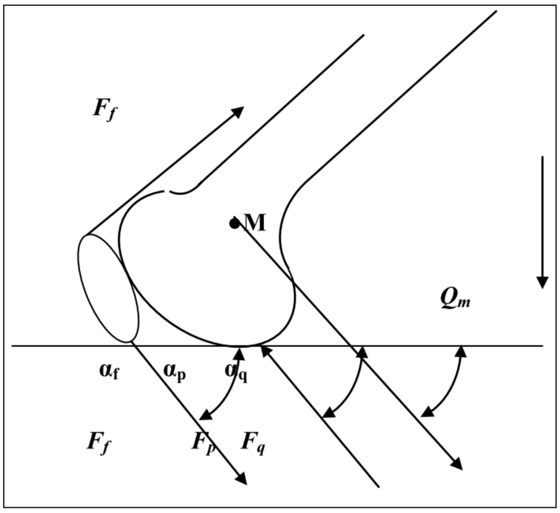

FIG. 7. FORCES GENERATED BY THE MAIN MUSCLES IN THE KNEE JOINT

$$F_p = \frac{F_q \cdot \cos \alpha_q}{\cos \alpha_p} + \frac{\cos \alpha_f}{\cos \alpha_p} \cdot \frac{F_q \cdot \sin(\alpha_q - \alpha_p)}{\sin(\alpha_f - \alpha_p)} + Q_m \cdot \cos \alpha_p$$

While F_q-force of the gastrocnemius

$$F_q = \frac{F_p \cdot \sin \alpha_p - F_f \cdot \sin \alpha_f - Q_m}{\sin \alpha_q}$$

DISCUSSION

The analysis of the kinematics of the knee joint from flexion to its full extension allowed us to (look at) and with moderate accuracy, mathematically describe (with the introduction of certain simplification concerning the superior articulation surface of the medial condyle of the tibia) the significant parameters of the motion of the medial condyle of the femur, over the superior articulation surface of the medial condyle of the tibia [10]. As a result, slide value as well as its geometrical derivatives such as velocity and acceleration have been estimated.

Based on the determined slide value, coordinates of the points of contact of the condyle and superior articulation surface of the medial condyle of the tibia as a function of the angle φ have been determined. By using the already determined coordinates of the point of contact *I** (for rolling and slide), and by adopting consecutive values of the angle φ, coordinates of the origin of the x_1y_1 coordinate system, and then the coordinates of the point "M" in the global system have been calculated. The calculated coordinates of the point "M" have been described with a degree 9 polynomial. The length of the path traveled by origin point of the gastrocnemius defined as "M" has been obtained through solving the polynomial mentioned above.

The description of the mechanics of the muscles involved in the motion of the extremity and determining the values of the forces generated by them during initiating the act of lifting human's own body mass.

CONCLUSIONS

The foregoing results and analysis of the mechanics of the muscles involved in motion of the human lower extremity-kinematics, estimated values of the forces generated by them, geometrical dimensions of the calcaneal tendon and the static uniaxial tensile trial of the calcaneal tendon, performed in order to obtain data concerning durability and longitudinal extension, became foundation for formulating the definition of spontaneous break of the calcaneal tendon. Based on the tests performed in vitro, (on natural postmortem material, acquired from fresh human corpses 12 hours after death) it has been found that the geriatric process significantly influences the durability of the Achilles tendon.

It was has been found that the resistance of the tendons of the left extremity to tension depends on individual's age and that for the Achilles tendon of the human right lower extremity is contained between 45 and 95 MPa [1,2,6,8-13], whereas for the left extremity, it is contained between 47 and 100 MPa. [1,2,6,8-13]. It has been found that (maximum) relative longitudinal extension of the dense regular connective tissue such as the tissue in the calcaneal tendon does not exceed 4%. The calcaneal tendon, unchanged pathologically, transmits very large dynamic forces generated by an organism in sudden situations. The tendon of the human left lower extremity is stronger than the tendon of the right lower extremity-this applies to right-handed people. From the age of 20, the durability of the calcaneal tendons in both extremities decreases asymptotically. The difference in the tendons' durability between right and left lower extremity persists and remains unchanged between the age of 20 and 35, yet from the age of 35 the difference decreases. Durability of the both tendons changes and they reach the same durability level around the age of 90 (graph on fig. 3).

As a result of the performed tensile test of the tendons, in the force range form 0 to the force extending the tendon, resulting from human's own body mass (for which the adopted mean value was 75 kg), it has been discovered that both imposing and relieving the load are realized practically along the same curve. In the force range dependent on individual's own body mass, the tendon behaves like a viscoelastic body. It has been found, that under the effect of imposing and relieving the load, processes, which immediately change its internal structure, occur in the tendon. These changes play an important role in alleviating effects of the dynamic load in the very first moment they occur. It has been found that the mechanism of taking over the load is connected to the fine structure of the tendon itself, composed of collagen fibers, out of which the most important role during taking over the increasing load is played by the macromolecules of tropocollagen [9].

Considering the knee joint as a mechanism, the path of the origin points of the gastrocnemius muscle exceeds the acceptable longitudinal extension of the tendon over 5 times. This fact is the cause of the calcaneal tendon's distal fibers' break. After performing the analysis of the kinematics of the knee joint in the aspect of pathomechanism of the break of the calcaneal tendon, while giving consideration to the result of the uniaxial tensile trial of the calcaneal tendon (in vitro), it is possible to formulate the following definition:

„The break of the calcaneal tendon of the human lower extremity occurs in the presence of the dynamic load. The muscles of the extremity are prepared to generate the force sufficient to put the body mass into motion, with a definite velocity and acceleration. All the muscle groups involved in supination and adduction of the extremities are put to work. Sudden uncoordinated spasm of the triceps surae muscle causes plantar flexion of the foot and causes stress in the section of the tendon, which is adequate to the generated force. The mass of the body is dynamically transmitted onto the femoral bone positioned at an angle of about 120° in relation to the longitudinal axis of the body. In order to maintain the balance of the body, the quadriceps femoris muscle contracts in a controlled and dependent on our will way, causing rotation of the femoral bone in the knee joint until the full extension. Because of the fact that both heads of the gastrocnemius muscle have their origin points on the femoral bone superior to the condyles, during rotation (extension) of the knee joint they move along the trajectory presented on (fig. 5). During this rotation, unrelaxed gastrocnemius moves around the condyles and the head of the tibia along the trajectory mentioned above (fig. 5), stretching the already tense tendon fibers. The movement path of its origins is in this case fivefold longer than the acceptable longitudinal extension, which for the collagen fibers of the tendon is 4%. Such state causes additional tension in already tense fibers, what consequently leads to the break of the external fibers of the calcaneal tendon."

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