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VIBROMECHANICAL DIAGNOSTIC CRITERIA FOR THE ACHILLES TENDON ACUTE TEARS

L.B. Maslov, V.I. Shapin

Theoretical and Applied Mechanics Department, State Power University of Ivanovo, 34, Rabfakovskaya Str., 153548, Ivanovo, Russia

Abstract: A new approach to analysing a physiological state of the human tissues is proposed. The research complex records amplitude-frequency characteristics of the Achilles tendon and calf muscle system. Resonance curves depend on physical parameters of the tendon conditioned by the real tissue state in the area of injury. One-dimensional biomechanical model is developed. The non-homogeneous space configuration of the tendon and muscles and the interior viscous friction are taken into consideration. The model describes stationary oscillations of the continuum stimulated by the local harmonious force. The forms of the resonance curves in the normal position of the foot, in the straightening and bending ones are established. The acute tear of the tendon is simulated and the comparison of the computer and real curves obtained by the research complex is made. A very detailed system of diagnostic criteria is developed.

Key words: oscillations, resonance, Achilles tendon, numerical model, fracture, computer simulation, diagnostics

Introduction

The accurate diagnostics of the Achilles tendon fractures and the permanent control over the rehabilitation process is the actual medical problem. Damages of the Achilles tendon significantly decrease physiological muscle strain, lead to serious functional disorders in neuromuscular apparatus or even to stable disability. Traditional methods of traumatology for determining the fracture of the tendon cannot provide the necessary reliability of the diagnostics. Statistic analysis proves that in 63% of such traumas the diagnostic mistakes are made. The modern techniques such as X-rays, radioisotopes or magnetic topography examinations are rather expensive and have restrictions to their application. That is why a new combined approach to analyse a physiological state of the human shank is considered.

Experimental approach

A stand for vibratory examination of the Achilles tendon state was suggested [1]. The device (Fig. 1) is composed of a platform with a firmly fixed vibrator (1), a splint for extremity fixation in the mid-physiological position (2), which is positioned in a firmly fixed table (3), a platform (4) and a dynamometer (5). The foot (6) is put on the platform and fixed with the belts. The platform has a rotator mechanism, the axis of rotation coinciding with the axis of the ankle joint (8). Excitation of mechanical oscillation is brought about by the electrodynamic vibrator (1) by means of a stock (9) with a tip (10), the oscillation is perpendicular to the axis of the Achilles tendon. A frequency and amplitude of oscillations are changed by means of a sound generator (11) and a power amplifier (12). Oscillation measurements are fulfilled by means of a vibroreceiver-accelerometer (13) which is fixed on the Achilles tendon close to the vibroconductor with the help of self-adhesive band. Parameters of the oscillation process, including resonance condition of the muscular-tendon

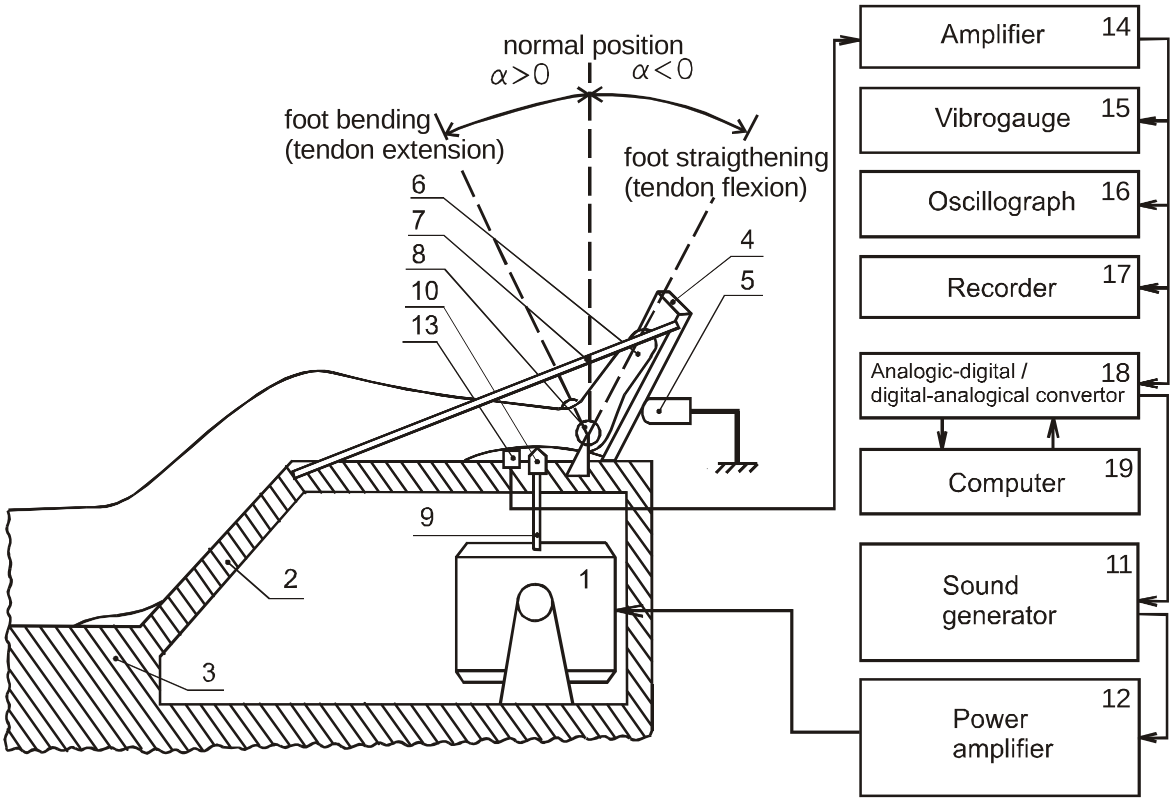

Fig.1. Scheme of the research complex for functional diagnostics of the shank tendon-muscular system.

complex, are registered after preliminary intensification (14) of the signal from the vibroreceiver by a vibrogauge (15), an oscillograph (16) and an automatic recorder (17).

The device is used in the following way. The patient lies on the table, the extremity is put on the splint and fixed by the belts on the level of the thigh and on the platform for the foot. Register-accelerometer is fixed by means of self-adhesive band on the level of projection of the mid-third of the Achilles tendon. The examination may be done in any foot position and any static effort of foot flexors and extensors.

The equipment records amplitude-frequency characteristics or resonance curves of the human tendon-muscular complex automatically for different kinds of vibratory excitation and for various positions of the foot. The characteristic describes the dependence between an excitation force frequency and the acceleration amplitude of the soft tissues oscillations in the fixed point on the calf muscle surface. A resonance curve depends on physical and mechanical parameters of the investigated object conditioned by the real tissue state around the injury.

Model description

Unfortunately, the serious problems has occurred while interpreting the registered resonance curves of the damaged tendon or muscle. This issue is connected with the general aim of the resonance vibratory diagnostics that consists in detecting a defect by analysing the resonance curves. The problem of defect identification is very complicated especially for biomechanical systems. In particular, it was shown that the amplitude-frequency characteristic and the mass of a system used traditionally for identification of mechanical models did not ensure a univalent determination of the model parametres even in conditions of restrictions to the model scheme [2]. Therefore, a special computer model is implemented for the estimation

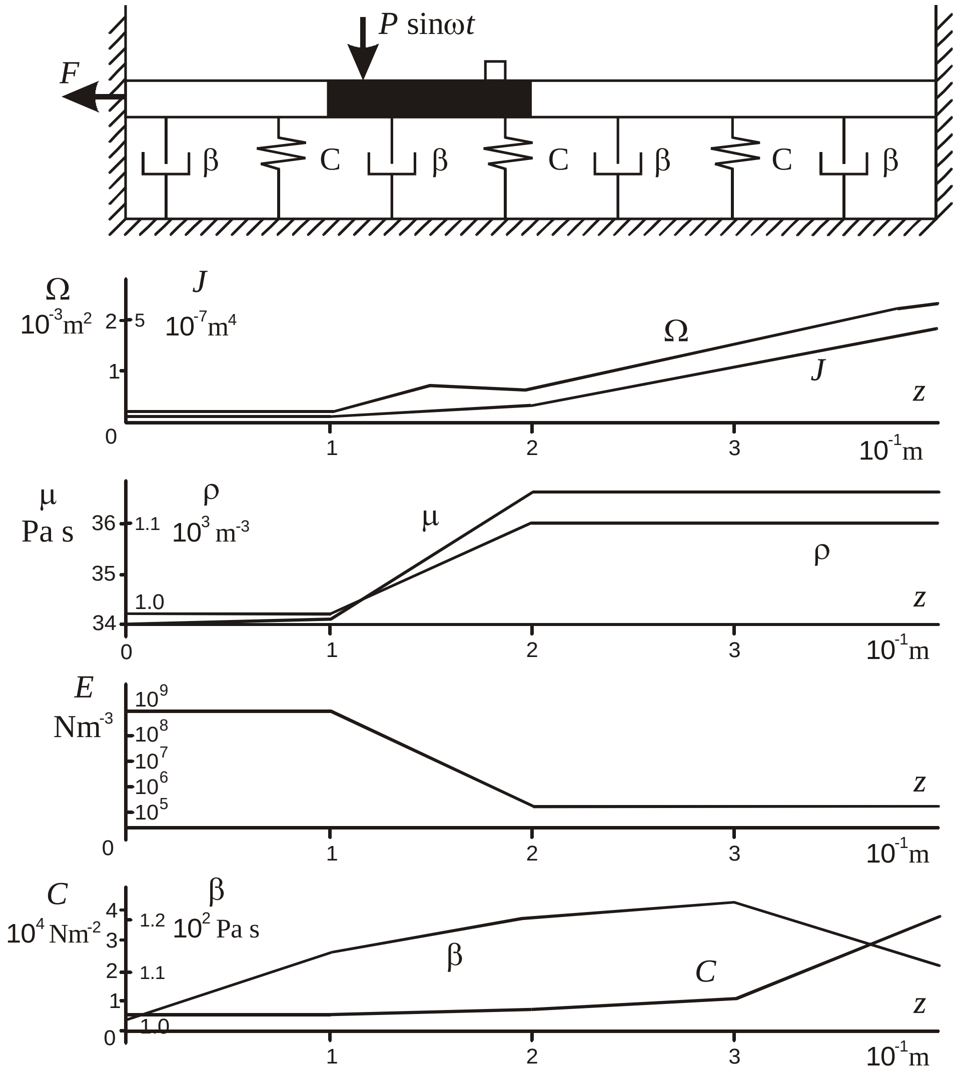

Fig.2. One-dimensional model of the shank tendon-muscular system and graphs of the model's physical-mechanical parametres values along the longitudinal axis z: area of the cross-section Ω, cross-section moment of inertia *J*, bar viscosity μ, density ρ, elasticity modules *E*, stiffness of the fundament *C*, viscous damping coefficient β of the fundament.

of the experimental data, for a priori prognosis of the bio-object behaviour and its dynamic characteristics in the cases of various kinds and different degrees of injury.

The non-homogeneous space configuration of the muscles and the other tissues around the tendon and the interior viscous friction are taken into consideration. At first one-dimensional model of the tendon-muscular complex is developed. The Achilles tendon with the soleus and gastrocnemius muscles are described as an elastic bar. The tibia and fibula bones with the soft tissues form a viscoelastic fundament. The lower head of the femoris bone and the rise of the heel bone are simulated as clamped ends of the elastic bar. The model is described by the non-homogeneous viscoelasticity equation [3]

$$\frac{\partial^2}{\partial z^2}\left(EJ\frac{\partial^2 u}{\partial z^2}\right)+\frac{\partial^2}{\partial z^2}\left(\mu J\frac{\partial^3 u}{\partial z^2 \partial t}\right)-F\frac{\partial^2 u}{\partial z^2}+\rho\Omega\frac{\partial^2 u}{\partial t^2}+\beta\frac{\partial u}{\partial t}+Cu=P(z,t)\,,$$

$$P(z,t)=P\,\delta(z-z_0)\ \sin(\omega t),$$

where $u(z,t)$ is the transverse displacement; *E* is the elasticity modulus of the bar; *J* is the cross-section moment of inertia; Ω is the area of the bar cross-section; ρ is the density of the tendon-muscular complex; μ is the bar viscosity recalculated for plane strain state; C is the stiffness of the fundament; β is the viscous damping coefficient of the fundament; F is the longitude stretching force due to foot rotation. The vibration excitation is modelled by the harmonious external force $P(z,t)$ applied to the Achilles tendon at the point z_0 with the vibration frequency ω. It influences the stationary oscillations of the system (Fig. 2).

The density ρ, the Poisson's ratio ν and the viscosity μ of the Achilles tendon are taken from the reference [4]. The elasticity modulus E is obtained from the experiment. The cross-section area Ω and the cross-section moment of inertia J are calculated using the results of the natural geometrical measurements of the shank and the data of topology of the shank taken from anatomic atlases.

The values of the stiffness of the fundament C are obtained for 5 cross-sections of the shank. The Achilles tendon with the soleus and gastrocnemius muscles are assumed to be a rigid body surrounded by the other soft tissues. So every shank cross-section is represented as a multiply connected area. Surface forces f_y on their boundaries in every cross-section are calculated by the boundary element method [5]. Then the equivalent force is computed as

$$Q_y = \oint_{\Gamma} f_y(q)\, d\Gamma_q, \quad q = q(x, y),$$

where Γ is the boundary of the shank cross-section. The stiffness of the fundament is calculated on the assumption of unique rigid body displacements

$$C = Q_y / u_y, \quad u_y = 1 \text{ mm}.$$

Lamb's formula for the case of rigid body movement in viscous liquid is used for calculation of viscous damping coefficient β of the fundament [6]

$$\beta = \frac{4\pi\mu_f}{b/(a+b) - 0.58 - \ln\left(\dfrac{\rho_f (a+b)V}{8\mu_f}\right)},$$

where μ_f and ρ_f are viscosity and density of the fundament taken from the reference [4], respectively; a and b are the half-axes of the ellipse as a model of the tendon-muscular complex cross-sections; V is the velocity of the body moved in the liquid. To avoid non-linear problem solving the value of V computed on the previous step of the frequency scanning is used for the calculations on the next step.

Numerical results analysis

The algorithm developed was used for modelling the normal state of the shank tendon-muscular complex of the chosen volunteer (the healthy man 25 years old) and the defect state with fresh Achilles tendon fracture. Basic differential equation was solved by the finite element method. An estimation of the longitudinal force in the neutral foot position was made by the solving the non-linear problem of the muscle straining from its non-deformed state to the actual one. A rotation of the foot influences the additional longitudinal force which was evaluated in the similar way. Nodal coordinates were recalculated automatically. The resonance curves of the idealised tendon-muscular model are shown in Fig. 3. Deviations of the first and second resonance frequency values from ones assessed experimentally are lying in the range of 1.7-4.2 %.

In clinical practice, one of the aims is to diagnose the tendon-muscular complex state. It means the finding out the presence of injury and its location and also the definition of kind and degree of injury. We have simulated the fresh (1-7 days after breaking) fracture of the tendon at the different distances from the heel bone and made the comparison of the computer characteristics of the injured tendon with the real curves obtained by the research complex. For the Achilles tendon fracture simulation, the complementary finite element with zero

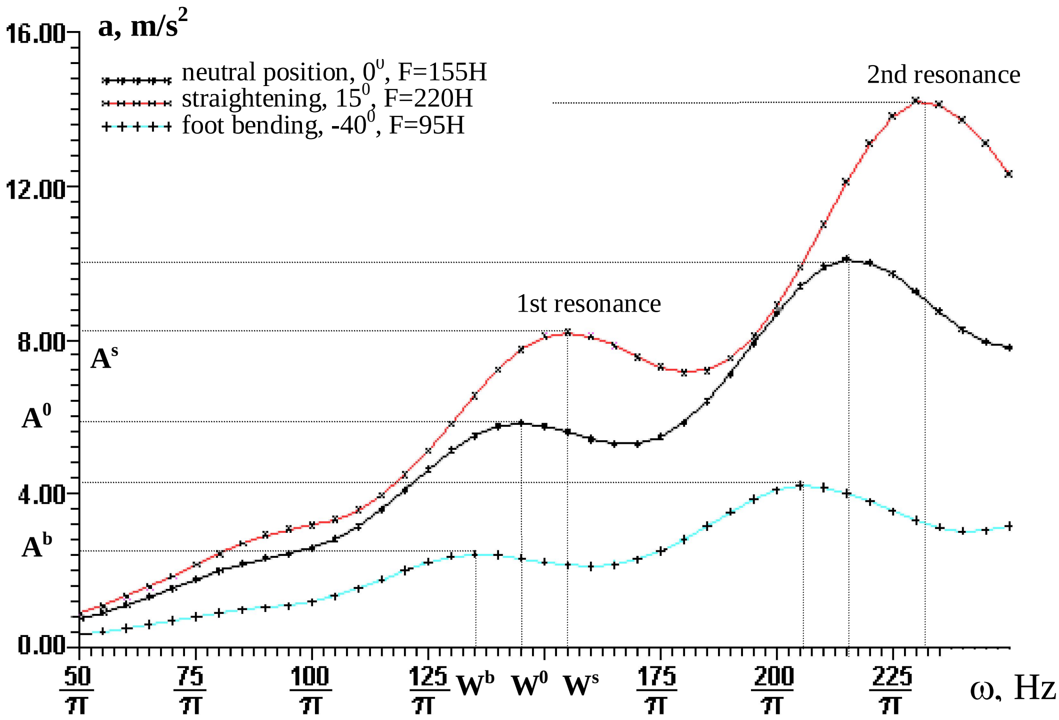

Fig.3. Simulated amplitude-frequency characteristics of the Achilles tendon-muscular system without defects at the distance of 12 cm from the heel bone (z=0.12 m) versus the different values of the foot rotate angle α and corresponding values of the longitudinal force *F*.

elasticity modulus was incorporated into the numerical model because the place of injury is ordinary filled by an inner liquid. The muscle's elasticity modulus decreasing is taken into consideration, too. The results of modelling are presented in Fig. 4. After analysis of them a very detailed system of diagnostic criteria was developed. All of them are mathematically expressed in terms of the values of resonance frequencies and amplitudes in three foot positions mentioned above. The most informative and reliable criteria of the acute Achilles tendon tear can be formulated as follows.

1) Alterations of frequency-resonance range of the tendon-muscular complex in the injured and contralateral (healthy) extremities in flexion (bending), extension (straightening) and neutral foot positions

$$\Delta\Omega^{s0} = (\Omega^{s0}_{inj} - \Omega^{s0}_{c/lat}) / \Omega^{s0}_{c/lat} ,$$
$$\Delta\Omega^{sb} = (\Omega^{sb}_{inj} - \Omega^{sb}_{c/lat}) / \Omega^{sb}_{c/lat} ,$$

where Ω^{s0}_{inj}, $\Omega^{s0}_{c/lat}$ are the differences of resonance frequencies in straightening and neutral positions for the injured and contralateral extremities; Ω^{sb}_{inj}, $\Omega^{sb}_{c/lat}$ are the differences of resonance frequencies in straightening and bending positions for the injured and contralateral extremities

$$\Omega^{s0} = W^s - W^0 , \qquad \Omega^{sb} = W^s - W^b,$$

where W^s, W^0, W^b are resonance frequencies in straightening, neutral and bending positions for injured and contralateral extremities (indexes «$_{inj}$» and «$_{c/lat}$» are not written for simplicity here and below). Diagnostic sign is the narrowing of the resonance-frequency range in the extension-neutral and extension-flexion positions: $\Delta\Omega^{s0} < 0$, $\Delta\Omega^{sb} < 0$.

2) Alterations of amplitude-resonance range of the tendon-muscular complex in the injured and contralateral extremities in bending, straightening and neutral foot positions

$$\Delta A^{s0} = (A^{s0}_{inj} - A^{s0}_{c/lat}) / A^{s0}_{c/lat} ,$$
$$\Delta A^{0b} = (A^{0b}_{inj} - A^{0b}_{c/lat}) / A^{0b}_{c/lat} ,$$

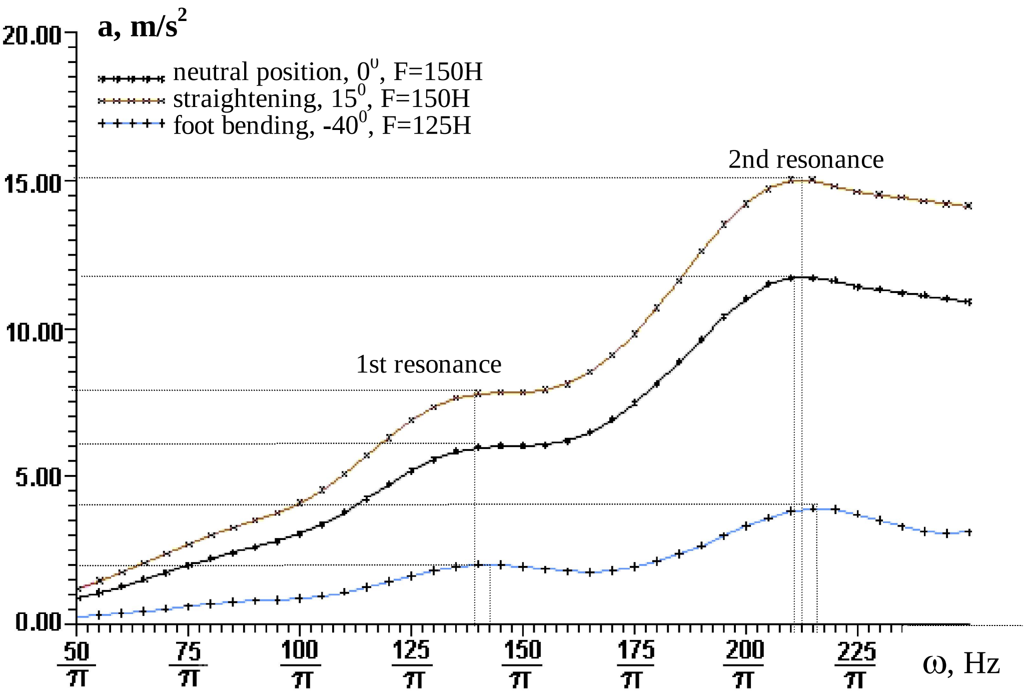

Fig.4. Simulated amplitude-frequency characteristics of the injured Achilles tendon-muscular system at the distance of 12 cm from the heel bone (z=0.12 m) versus the different values of the foot rotate angle α and corresponding values of the longitudinal force F. The point of breaking is located at the 6 cm distance from the heel bone (z=0.06 m).

where A^{s0}_{inj}, $A^{s0}_{c/lat}$ are the differences of resonance amplitudes in straightening and neutral positions for the injured and contralateral extremities; A^{0b}_{inj}, $A^{0b}_{c/lat}$ are the differences of resonance amplitudes in neutral and bending positions for the injured and contralateral extremities

$$A^{s0} = A^{s} - A^{0}, \quad A^{0b} = A^{0} - A^{b},$$

where A^{s}, A^{0}, A^{b} are resonance amplitudes in straightening, neutral and bending positions for injured and contralateral extremities. Diagnostic signs are the narrowing of the extension-neutral amplitude range and the rise of the neutral-flexion amplitude range: $\Delta A^{s0} < 0$, $\Delta A^{0b} > 0$.

3) Alterations of the quantity of peaks on the resonance curves in the injured and contralateral extremities in bending, straightening and neutral foot positions

$$\Delta n^{b} = (n^{b}_{inj} - n^{b}_{c/lat}) / n^{b}_{c/lat}, \quad \Delta n^{0} = (n^{0}_{nj} - n^{0}_{c/lat}) / n^{0}_{c/lat}, \quad \Delta n^{s} = (n^{s}_{inj} - n^{s}_{c/lat}) / n^{s}_{c/lat},$$

where n^{b}_{inj} , $n^{b}_{c/lat}$, n^{0}_{nj} , $n^{0}_{c/lat}$, n^{s}_{inj} , $n^{s}_{c/lat}$ are the numbers of peaks on the resonance curves in every foot position for the injured and contralateral extremities. Diagnostic signs are smoothing of the resonance curve and decrease of the number of resonance peaks in every foot position: $\Delta n^{b} < 0$, $\Delta n^{0} < 0$, $\Delta n^{s} < 0$. This sign is theoretically observed as smoothing of the calculated characteristics.

For the simulated tendon tear with the amplitude-frequency characteristics shown in Fig. 4, the numerical values of the frequency criteria calculated by utilising the non-defective resonance curves of the contralateral extremity (Fig. 3) are equal to

$$\Delta\Omega^{s0} = -100 \text{ \% and } -83 \text{ \%}, \quad \Delta\Omega^{sb} = -112.6 \text{ \% and } -120 \text{ \%}$$

for the first and second resonances, respectively. And the amplitude ones are equal to

$$\Delta A^{0b} = 14 \text{ \% and } 32.2 \text{ \%}, \quad \Delta A^{s0} = -31.3 \text{ \% and } -15 \text{ \%}.$$

To make a conclusion on the tendon-muscular complex state we should take into consideration every criterion together with its partial significance. So we have also introduced a point-system (k_i) for evaluating the diagnostic signs depending on the their types and meanings. Each of the most significant frequency criteria can take 2 points if it is fulfilled and 0 if not. The other criteria can have values between 1 and 0 depending on the same conditions.

Reliability of presence of the tendon tear is characterised by the total quantity of diagnostic signs, the sum of percents of all the diagnostic signs (S) and the reliability index (I), which are calculated by the formulas

$$S = \Delta\Omega^{s0} + \Delta\Omega^{sb} - \Delta A^{0b} + \Delta A^{s0} + \Delta n^{b} + \Delta n^{0} + \Delta n^{s},$$

$$I = \sum k_i / K \times 100\ \%,$$

where K is the maximal possible quantity of points k_i, here $K = 9$. The greater are these magnitudes, the more reliable is the Achilles tendon tear.

Discussion

The examinations using the developed equipment was made in the War Veteran Hospital (Ivanovo, Russia). Over 100 amplitude-frequency soft tissues characteristics of damaged and normal extremities were examined. Amplitudes and frequencies of resonance oscillations were used as informational parameters. The statistical analysis of the data showed the following parameters of the first resonance for pushing and non-pushing extremities, respectively: resonance frequency 43.1±2.24 and 45.1±1.12 Hz; energy dissipation factor 2.2±0.09 and 2.1±0.08. These characteristics reflect stiffness of tendon-muscular complex and its interaction with surrounding tissues.

We have applied the criteria system described for investigating the shanks of 14 patients with acute Achilles tendon tears. All of them underwent the vibration examinations and the following surgical operations in the period from 1 to 5 days after tendon breaking. The tendon edges divergence (diastasis) averaged one centimetre. The injures were located over the heel bone in the range of 4-7 cm.

The investigation has showed that in patients with acute Achilles tendon tearing $\Delta\Omega^{s0}$=1.8±0.1 points, $\Delta\Omega^{sb}$=1.9±0.1 points. These signs are the most significant characteristics of acute subcutaneous Achilles tendon tear. The characteristics of lesser importance are diagnostic signs concerning alterations in peaks quantities in amplitude-frequency characteristics of the tendon-muscular complex of the injured and contralateral extremities in flexion, extension and zero foot position: Δn^0 was 0.9±0.1 points; Δn^b and Δn^s were 0.8±0.1 points each; the same concerned ΔA^{0b} and ΔA^{s0}. The sum of points ($\sum k_i$) of the above mentioned signs in this group of patients was equal to 7.8±0.3 points with the possible maximum of 9 points. This sum and the reliability index (I=86.5±3.1%) confirm the diagnostic value of the suggested method. The intensity of diagnostic signs in absolute calculation (total percent S) was equal to 369 ± 14%. The large magnitudes of S prove the Achilles tendon tear.

Conclusions

The elaborated method of diagnosing functional condition of the tissues under the influence of low-frequency local vibration allows to diagnose a subcutaneous Achilles tendon tear, the reliability being 86.5±3.1%. Thus, the elaborated method and automatic equipment for vibrodefectoscopy of the tendon-muscular complex of the lower leg allow to introduce into clinical practice other effective diagnostic signs of the tendon condition in the regime of local vibratory examination and predict alterations in the amplitude-frequency characteristics of the soft tissues system for various types of injuries.

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ВИБРОМЕХАНИЧЕСКИЕ ДИАГНОСТИЧЕСКИЕ ПРИЗНАКИ СВЕЖИХ РАЗРЫВОВ АХИЛЛОВА СУХОЖИЛИЯ

Л.Б. Маслов, В.И. Шапин

В статье рассмотрен новый подход к определению физиологического состояния мягких и твердых тканей человека, основанный на анализе динамического отклика биомеханического объекта на гармоническое возбуждение с частотой, плавно меняющейся в заданных пределах. Разработан медицинский комплекс для вибрационного обследования состояния ахиллова сухожилия и экспериментально обнаружены динамические реакции мышечно-сухожильной системы голени человека на локальное вибрационное возбуждение. Качественный характер и числовые параметры регистрируемых амплитудно-частотных характеристик существенным образом зависят от действительного состояния тканей в области травмы. При этом установление ясной взаимосвязи между характерным дефектом системы (в нашем случае - свежим разрывом ахиллова сухожилия) и наблюдаемыми изменениями в амплитудно-частотных характеристиках сухожильно-мышечного комплекса невозможно без анализа дефекта на какой-либо модели. В разработанной конечно-элементной модели ахиллово сухожилие вместе с прикрепленными к нему камбаловидной и частично икроножной мышцами представлено в виде стержня переменного сечения, плотности и модуля упругости. Мягкие ткани, окружающие сухожилие и лежащие на большой и малой берцовой кости, представляют упруго-демфирующее основание, характеризующееся коэффициентами жесткости и демпфирования. Внешнее возмущение представляет гармоническую силу, приложенную локально в фиксированной точке на продольной оси стержня, и вызывающую стационарные поперечные колебания системы в саггитальной плоскости. Установлен вид идеальных резонансных кривых сухожильно-мышечной системы голени при различных углах поворота стопы (нормальное физиологическое положение, максимальное разгибание и сгибание). Проведено моделирование свежего разрыва ахиллова сухожилия, и разработана система диагностических признаков, включающая в себя семь основных механических параметров, получаемых расчетным путем по значениям резонансных частот и амплитуд в различных положениях стопы пациента. Это дает врачу, не обладающему глубокими знаниями в области механики, возможность по экспериментальным данным достаточно быстро и точно поставить диагноз о наличие разрыва сухожилия. Разработанное диагностическое оборудование и методика анализа регистрируемых резонансных кривых прошли успешную апробацию в госпитале ветеранов войн г. Иваново на базе межвузовской лаборатории биомеханики. Библ. 6.

Ключевые слова: колебания, резонанс, ахиллово сухожилие, численная модель, разрыв, компьютерное моделирование, диагностика

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