Tensometry of soft biological tissues with manipulation robot

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Abstract. A method of automating the process of controlling strain gauge measurements of parameters of elastic objects using a manipulation robot is considered. The subjects of the study are elastic objects whose structure is multilayered, and individual layers have the properties of heterogeneity and nonlinearity. An example of such objects is soft biological tissue. Currently available diagnostic tools have insufficient accuracy because of the fact that the measurement results significantly affected by the errors arising from the explorer’s errors during automated diagnostics and accidental interference on the part of the research object. Strain gauge measurements relate to the subject area of assessment of the state of elastic structures. The paper discusses the implementation of the algorithm for controlling the procedure of tensometric measurement of soft biological tissues, proposes engineering solutions to eliminate these drawbacks. Elimination of inaccuracies in the development of force and speed tasks causing the greatest errors achieved by using a manipulation robotics equipped with a strain gauge measurement device. A prototype of a robotic system equipped with a power sensor, a compensation mechanism and a software control algorithm is given. The results of the study are presented in the form of characteristic dependences of forces on displacements.

1. Introduction

In problems, where position-force control (PFC) is applied, there are pneumatic, potentiometric, binary force sensors of known design [1]. These sensors are used in feedback in case of force control. While we establish feedback on the force, such a sensor can be used not only for the PFC, but also for strain gauge measurements of soft biological tissues [1, 2, 3]. From the point of view of mechanics, the task of controlling a manipulation robot is to deform certain sections of soft biological tissues (SBT). They are skin, muscle and tendons. The force-controlled robotic system is equipped with a manipulator drive system which guides the tool flange along the tool axis until the force measured by the sensor along the tool axis is equal to the set value [4]. However, unlike the indirect effect on the SBT through the levers of bones and joints, when the deformation directed along the muscles, when manipulating the SBT, the tool directly affects the muscle, mainly in the transverse direction, which discussed in detail in the article.

2. Control object model at tensometry
To measure the parameters of soft biological tissue, there is currently a variety of sensors called myotonometers. There are electromechanical myotonometer Uflyanda, Myoton-2 and mechanical myotonometer Sirmai, Dubrovsky [5]. In the case of measuring the force with a compliance of the analyzed material in a few millimeters, the deformation of the elastic element of the force sensor can be measured with a strain gauge sensor. Figures 1 and 2 show the design of a single-component force sensor with spring elastic elements and a strain gauge of the spring deformation [6].

![Figure 1. Muscle tone measurer (external view of the device installed on the robot flange)](image1)

![Figure 2. Instrument of the measurer in contact with soft tissues, where: 1 - biological tissue, 2 - tool, 3 - force sensor, 4 - robot, 5 - strain gauge sensor, 6 - spring)](image2)

Soft biological tissue has been chosen as an object of analysis, and muscle tone (MT) chosen as a registered parameter. Muscle tone is one of the fundamental characteristics of a muscle, reflecting its properties and the state of the neuromuscular apparatus. Muscle tone is a long-lasting muscle tension, which is not accompanied by fatigue and provides a certain position of the body in space. There are muscle tone in a calm state (plastic tone) and tense state (contractile tone) [7].

Muscle tone characterizes the elastic properties of soft tissue and therefore defined as its “stiffness”, from the dependence on the displacement $\Delta$ at deformation on increasing effort $F$ on the SBT, which causes this deformation (figure 3). For the SBT and the muscles, it is a non-linear dependence with a variable coefficient of elasticity (stiffness). The dimension of this coefficient is N/m.

If the SBT on the linear sector has elasticity $k_1$ (figure 3 (a), and the force sensor in the linear sector has a slope $k_1$, then their serial connection in the design of the force sensor is represented by the characteristic as in figure 3 (b), and in the linear sector the equivalent slope $k$ is equal to:

$$k = \frac{k_1 \cdot k_2}{k_1 + k_2} \quad [8].$$

![Figure 3. Models of contact interaction between the tool of the force sensor and the SBT and](image3)
characteristics: a) $k_1$ - SBT, $k_2$ - springs, b) SBT and springs.

Skeletal muscles in statics are a visco-elastic material by mechanical behavior. The calculated value $k$ can be fixed through an elastic measuring element (spring) attached to the movable element of the strain gauge (figure 1). The signal from the strain gauge $U$, proportional to the deformation of the spring, converted into a code one, inputting to the robot control system. To describe the processes occurring in ST as in the elastic element, Hooke's law is valid [1]:

$$k = \frac{F}{\Delta},$$

where $F$ is force equal to external load applied perpendicular to cross section of SBT; $k$ is coefficient of cross section; $\Delta$ is deformation of SBT. The growth rate of curve $F(\Delta)$ is another characteristic feature.

$$tg\alpha = \frac{dF}{d\Delta},$$

where $dF$ is the increment of effort; $d\Delta$ is the deformation increment; $\alpha$ is the angle of inclination of the tangent to $F(\Delta)$. The steepness of the characteristic $F(\Delta)$ is variable and depends on the deformation of the SBT, its thickness, on the dimensions of the contact surface of the tool. The elasticity of the tissue in terms of thickness is non-uniform, the upper part - the fat layer is the softest. In addition, the steepness of the characteristic depends on the degree of muscle tension. The range of values of the steepness for different MBT is wide. For a wide soft layer of tissue, the values of the coefficient of elasticity on the linear section are of the order of 0.01 N·mm⁻¹, for the stressed thin-layer section are 100 N·mm⁻¹.

3. The model of the control system at tensometry of SBT

The registration of muscle tone is performed by installing a sensor instrument on an SBT sector, with continuous (or delayed) tool immersion in the SBT in a static mode, when steady-state values of forces and strains are being measured (figures 4 and 5).

Immersion levels are set by software offset by $\Delta$ in mm. With each immersion in the memory of the measuring system the voltage level $U$ fixed on the strain gauge. While studying the SBT and the muscles, a miotonogram with the coordinates is obtained: on the abscissa axis - the depth of immersion (muscle
hardness), on the ordinate axis the increasing force, for each projection on the miotonogram you can get the coefficient of elasticity. The dimension of this coefficient is N·mm⁻¹.

The depth of immersion of the tool in the muscle is not more than 18 mm. The characteristics of the registration process were determined on the basis of the characteristics of a single-component force sensor FC2231. Depth measurement error would be up to 0.5 mm. The error in determining the force is up to 3 grams with a force of up to 750 grams and no more than 10 grams with a force of up to 2000 grams. Power supply is 5 volts. The measurement results are inputting into a computer through the COM port and processed with a program that represents them in graphical and tabular forms.

On the graph in figure 5 it is possible to obtain information about different values of the elasticity of the tissues. Track the dynamics of changes in elasticity can be on the values of MT, as well as the deviation of the amplitudes of the voltages at each step.

The sensitive element of the force sensor is a spring. For a linear spring, its deformation Δ in statics is proportional to the force of the $F_{ELASTIC}$ with the coefficient of elasticity of the $K_{SPRING}$ [9]:

$$F_{ELASTIC} = -\Delta \times K_{SPRING}, \quad (4)$$

After spring calibration, for example, using a dynamometer, you can recalculate its deformations into force. To diagnose the elasticity of the soft tissue, the arm of the robot must move by the value of $x$, the spring is compressed by the value of $\Delta$, and the soft tissue by the value of $\delta$. For the calculated force $F_{ELASTIC}$, soft tissue deformation $\delta$ is a measure of the elasticity of soft tissue $K_{ST}$:

$$K_{ST} = -\frac{F_{ELASTIC}}{\delta}, \quad (5)$$

Let us establish the relationship between the values of $x$, $\delta$ and $\Delta$, since the program shift is determined by the formula:

$$x = \Delta + \delta, \quad (6)$$

Therefore,

$$x = \Delta + \frac{F}{K_{ST}} = \Delta + \left(\frac{\Delta \times K_{SPRING}}{K_{ST}}\right) = \Delta \times \left(1 + \frac{K_{SPRING}}{K_{ST}}\right), \quad (7)$$

where $x$ is the programmed movement of the robot; $\Delta$ is the deformation of the spring measured by the induction sensor and is a measure of the force; $K_{SPRING}$ - spring stiffness, calculated by calibration.

Let us calculate the coefficient of elasticity of soft tissue:

$$K_{ST} = \Delta \cdot \frac{K_{SPRING}}{x - \Delta}. \quad (8)$$

Due to the straight-line nature of the robot's movement at tensometry, one can consider a drive, whose movement in the horizontal direction causes a tool pressure on the SBT along the Z axis of the tool coordinate system [10]. Then the force of gravity will not affect the pressure. Excluding the viscous component, due to the low approach speeds, putting $q = z$:

$$U = iR + C_v \cdot \frac{dz}{dt}, \quad (9)$$

$$M \cdot \frac{d^2 z}{dt^2} = F_d - F, \quad (10)$$

$$F_d = C_f \cdot i, \quad (11)$$
where $U$ is the voltage applied to the DC motor, $i$ is the armature winding current of the DC motor, $R$ is the resistance of the armature winding, $C_v$ is the coupling coefficient between speed and electrical driving force, $z$ is the real displacement of the manipulator along the tool axis, $z_e$ is the surface relief ST, $M$ is the mass of moving parts of the manipulator, $F_d$ is the driving force, $F$ is the real force of interaction with the external environment, $C_f$ is the coupling coefficient between the current and the driving force, $K_z$ is the coefficient of the proportional regulator for the position, $K_f$ is the coefficient of the proportional controller for force. Accordingly, the block scheme of a similar model is shown in figure 6.

![Figure 6](image)

**Figure 6.** The structure of the model of control of the manipulator at tensometry.

At the initial moment of time, the tool touches the surface of the MBT and then immerses into it. The presence of an elastic element in the structure of the control system provides compensation in the distribution of sharp forces.

4. Measurement of the parameters of the SBT by manipulation robot

Investigating the elasticity of the soft tissue with the use of the modernized robot RM-01, an experiment on tensometry has been carried out on the quadriceps muscle of the thigh. Immersing of a tool was carried out in two stages with repetition. The first stage was in the study of the relaxed muscle, the second stage was in the study by the same method of strained muscle.

An example of this can be the experimental curves $F=f(\Delta)$ obtained on soft tissue while immersing and leaving the tool in areas with different elasticity, reflected by the distance of the graphs from each other (figure 7).

![Figure 7](image)

**Figure 7.** Graph of dependencies $F=f(\Delta)$, relaxed (1) and strained (2) quadriceps thigh muscle.
The graphs reflect the main difference between the studied strained and relaxed muscles, different levels of amplitude values in elasticity.

The strained muscle curve (highlighted in red) reaches its maximum stress value in the same number of steps $\Delta$. Tensometry was held for a short time period, close to the actual operation of the tool on the surface of the soft tissue at the manual method of measurement.

In order to estimate changes in the parameters of the SBT, there are not necessary absolute measurements, but differential, considering set of points at different periods of time associated with rehabilitation processes (for example, rehabilitation therapy).

With the improvement of the functional state the amplitude and muscle tone index increase (the difference between strain and relaxation). With fatigue the amplitude decreases, the tone of rest increases.

There are many empirical indicators [11] applied to integral estimates for a given curve. Such a methodological approach allowed us to formulate a semantic function that adequately reflects the degree of MT at rest and during the mobilization of the SBT.

One of the stages of the continuation of work is the development of a tensometry methods using a robot that would allow an accurate estimation of the parameters of the SBT [12, 13].

5. Conclusion
The objectivity of tensometry of soft biological tissues is due to given forces and speeds, which will allow you to work out a controlled multi-link manipulation robot using the last drive as a force sensor. The presence of a compensation mechanism can improve the safety of tensometry. The obtained research results allow to analyze static and dynamic indicators, including various integral evaluations.

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