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Use of modern tribology approaches for correcting the behaviour of adaptive biomechanical friction units

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ABSTRACT

Purpose: Functioning of mechanical system friction units is characterized by the ability of their self-adaptation under the influence of external loads. Referring to this phenomenon it becomes possible to provide the necessary correction of the work of friction units being parts of artificial and natural tribosystems.

Design/methodology/approach: As an approach used to solve the above problem, an expansion of the function describing friction unit parameters in a given basis with further refinement of the solution in accordance with the functional optimization is proposed.

Findings: The received ratios allow solving the problem of adaptive control of friction units functioning when they are incorporated into the biomechanical systems.

Practical implications: Using approaches developed in the present work, a pattern for the gradual adjustment of instep supports for the restoration of normal weight distribution in the human foot is presented.

Originality/value: Novel approaches to the methodology of solving the problem in regard of managing the load condition of biomechanical tribosystems by their commanded control over time are offered.

Keywords: Biomechanical friction units, Adaptive behaviour and control, Inverse problems in mechanics

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

Friction units are one of the most important elements in mechanical systems, components of which stay in the interaction. In this case, the general laws of friction processes nature such as the reduction of friction and wear coefficient (including its abnormally low values if lubricants are present), surface roughness stabilization, gradual decrease in the energy costs necessary for a contact pair to perform the work in a steady operation mode are characteristic both for the artificial friction units (for instance in various mechanisms) and natural ones, i.e. human and animal joints [1].

This fact allows us to consider functioning of friction pairs of any origin under the unified and generalized perspectives and enables using approaches as well as results that have proven to be bountiful for solving problems in mechanics when analysing the behaviour and correction of the work of human and animal joints.

One of such approaches in tribology is the consideration of any functioning friction unit as an open thermodynamic system characterized not only by various complex interconnected processes but also by such an important feature as the possibility of self-organization and self-adaptation, that is, it possesses the properties of a cybernetic (self-regulating) system capable to adapt to the operating conditions to a greater or lesser extent through changing the structure of contact materials, lubricating film, lubrication modes, stressed state, and, as a response reaction, adjust the degree of adaptation [1-3].

In this regard, it can be a priori assumed that any dynamic system (biological or artificial), which includes a friction unit is also a response reaction system. The intended correction of the system work makes it possible to regulate the parameters of a given friction unit, which functioning in its turn significantly affects the performance characteristics of the entire system.

It is worth to note that such formulation of the problem is rarely used in tribology since the practical self-adaptation during the work of friction mechanical systems is a very complicated engineering and scientific issue.

2. Generalized formulation of the problem

Let us consider some dynamic system S, which consists of N friction units.

Let us represent functioning of system S as functional G, which depends on M following input parameters, – $x_1,\ldots,x_M$, L internal parameters – $y_1,\ldots,y_L$, which may change over time $(x_1 \equiv x_1(\tau),\ldots,x_M \equiv x_M(\tau)$, $y_1 \equiv y_1(\tau),\ldots,y_L \equiv y_L(\tau))$:

$$G(\tau) \equiv G(x_1,\ldots,x_M,y_1,\ldots,y_L). \tag{1}$$

Let us allocate the subset of parameters $q_1,\ldots,q_K$ describing the condition of friction systems among the parameters set $y_1,\ldots,y_L$. Other parameters will be denoted as $r_1,\ldots,r_S$:

$$\{y_1,\ldots,y_L\} = \{q_1,\ldots,q_K\} \cup \{r_1,\ldots,r_S\}. \tag{2}$$

Thus, the functional (1) will be as follows:

$$G(\tau) \equiv G(x_1,\ldots,x_M,r_1,\ldots,r_S,q_1,\ldots,q_K). \tag{3}$$

Let us accept that $G^*(\tau)$ is the most desirable trajectory of the dynamic system S. This condition can be described by the following relations:

$$\lim_{\tau\to\tau_1}\left|G^*(\tau)-G(\tau)\right| = 0 \tag{4}$$

or

$$\frac{1}{\tau}\int_{\tau}\left|G^*(\tau)-G(\tau)\right| = 0. \tag{5}$$

The relation (4) indicates that upon reaching a given time the dynamic system function in an intended way (for example, the biomechanical system rehabilitation will occur), and the relation (5) describes the fact that the system trajectory becomes stabilized in the studied interval.

Consequently, formulating of the problem of the search to adapt friction system components is reduced to the following: the search for such functional subset $\{q_1,\ldots,q_K\}$ out from the allowable set $\{Q_1,\ldots,Q_K\}$, which at given values $\{x_1 \equiv x_1(\tau),\ldots,x_M \equiv x_M(\tau)\}$ and $G^*(\tau)$ satisfy relations (4) or (5).

Now, let us consider possible ways to solve the above problem. Papers [4,5] describe the most practically simple and tested method. To calculate the required parameters $\{q_1,\ldots,q_K\}$ the set of functions $\left\{\{g_1^i\}_{i=1..P1},\ldots,\{g_k^i\}_{i=1..Pk}\right\}$

(a set of elementary, i.e. "classical" functions, which are mostly mutually perpendicular) is introduced. Using them and the method of linear additive superposition those approximations of parameters $\{q_1,...,q_K\}$ (Fig. 1) are chosen, which best satisfy ratios (4) or (5).

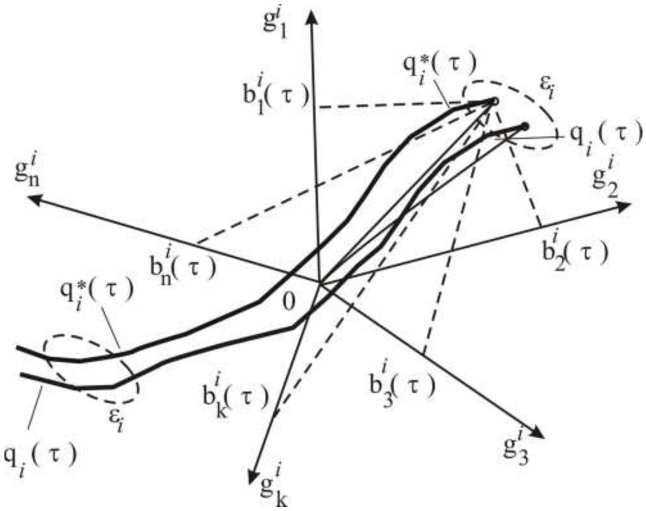

Fig. 1. Pattern of functional approximation of the function trajectory using linear superposition in a given basis: $\{g_1^i,...,g_n^i\}$ – basis functions; $\{b_1^i(\tau),...,b_n^i(\tau)\}$ – time coefficients; $q_i(\tau)$ – trajectory of the function to be approximated; $q_i^*(\tau)$ – approximation of the trajectory of function $q_i(\tau)$; ε_i – required accuracy

3. Model solution of the problem on controlling of adaptive biomechanical friction units

In a plenty of publications the work of biomechanical friction units (joints) in a human has been analysed though no common theory has been available yet.

Significant success gained at the intersection of biophysics, biotribology and orthopaedics to a large extent confirm the fundamental assumptions of the molecular-mechanical theory of friction on the possibility to apply methodology used to evaluate the actual area of a contact site, rigidity, the third body concept, and hypothesis of film fasting in the study of human joints as friction units.

Modern concepts of joint lubrication are considered as a separate component of the tribological system (human joint), i.e. a lubricating film, which mechanically, thermally and electrically interact with human biological tissues [6]. It looks like a liquid crystal with layers parallel to the friction surfaces. Articular cartilage is a fibrous gradient porous structure filled with the liquid containing electrostatic charged particles. This complex system, which functioning includes the formation and circulation of lubricating fluid as well as the disposal of wear products is connected to the nerve centre, which controls its work. The onset of joint disease occurs when the adaptive unit does not work properly. There are numerous reasons for this but the most important is malfunctioning of joint surrounding muscles and the nerve knot that controls a biomechanical friction unit [1,7]. One of the possible ways of correcting the work of a friction unit is the targeted influence affecting specified nerve endings and human muscle in order to restore the joint metabolism and, as a result, its normal use. A similar problem arises in the treatment of flat feet in humans due to the muscle relaxation as well as problems with feet joints [7].

Consider the formulation of a model problem of the adaptive correction of a friction unit, i.e. human foot. Let the biological object (a human), for some reason, has difficulties with the distribution of weight per the foot surface due to flat feet [8,9]

We offer the following mathematical formulation to solve this problem.

At a reference time point let the distribution of foot load on the inner surface of shoes be $p(z,\tau_0)$, where z is a variable describing the inner surface of shoes and τ_0 is a reference time point. The desired (necessary) distribution is $p^*(z)$.

The task is to pick up such a parameter of a shoe inner surface profile $L(z,\tau)$ to receive $p(z,\tau)\to p^*(z)$ or $\left|p(z,\tau)-p^*(z)\right|\to 0$, where $p(z,\tau)$ is the load distribution and τ is the reference time point.

To solve this problem we offer the following algorithm:

1. Using functions of the load distribution $p(z,\tau_0)$ and $p^*(z)$ we can define the foot surface profile as $L(z)=L_1(z)\cup L_2(z)$, where $L_1(z)$ is a part of the foot region, where the load should be present, $L_2(z)$ is the foot region with no load present.
2. We vertically increment the profile region $L_2(z,\tau)$ until $p(z,\tau)_{L_1(z)}\approx p^*(z)_{L_1(z)}$. From the applied

mathematics perspective this expression can be represented as searching such set of coefficients $\{b_1(\tau),...,b_S(\tau)\}$ for the expression $L_2(z,\tau)=\sum_{i=1}^{s} b_i(\tau)\cdot f_i(z)$, which satisfy the achievement of relation $\left|p(z,\tau_k)-p^*(z)\right|\le\varepsilon$ at given time parameter τ_k and accuracy ε. The value τ_k is defined by the physiological features of the foot structure of a specific person.

From the medical practice perspectives, these recommendations are equivalent to fitting of an instep support used to correct flat foot development. The proposed by us approach is based on the gradual selection of an instep support surface function taking into consideration the preferable adjustment of coefficients $b_i(\tau)$. Then, using 3-D prints of a shoe inner surface it is possible to adjust the instep support preferable profile for each person individually (subject to his/her body parameters) and in this manner to affect the biomechanical friction unit, i.e. human foot.

The development of the above research trend is relevant when using not only mechanical but also electromechanical instep supports, which through electrical stimulation of nerve endings are capable to restore both muscle tones and the work of nerve centres of human joints responsible for their functioning [10].

4. Conclusions

1. Based on the analysis of the dynamics of friction units an approach for assessing functioning of friction biomechanical units as adaptive systems demonstrating the ability to self-regulation and self-repair depending on the conditions of their operation is considered.
2. Methods of mathematical modelling of such objects are proposed based on calculating of optimal functional dependences in a given elementary basis of functions.
3. It has been shown that solving the problem of improving the functioning of biomechanical friction systems is possible through the use of controlled adjustment of additional mechanical loads based on the approaches of digital medicine and orthopaedics.

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