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INVESTIGATION OF AMPUTEE WALKING ON THE ABOVE-KNEE PROSTHESIS

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Abstract

One of the most imortant criteria of evaluation of a prosthesis performance is the degree of amputee's fatigue during walking.

The purpose of this work is to estimate the energy expenditures of an amputee in gait. Keeping this aim in mind a mathematical model of a nine-link biokinematic chain which corresponds to the amputee walking was composed. The equation system has been used for computer calkulation of the moments of muscle forces applied to the lower extremity joints in sagittal plane. The obtained information was used as a ground for the definition of the values of powers and works released in the extremity joints.

The initial data was collected as as the result of experiments with amputee walking on prostheses of different designs.

Introduction

Inevitable consequence of amputation is loss of functions of weight bearing in gait and sensoe feedbacks. The modern types of the prosthesis are able to recreate the function of proper weight bearing and propulsion, but it does not compensate the muscle force losses. That is why the actual problem nowdays is the working out of the prosthesis designs with external power sources , parameters of which may be obtained on the basis of general knowledge of energy expenditure in gait. One of the main requirements to the modern type of prosthesis is the performance of gait with minimum energy losses.

This paper is devoted to the evaluation of energy losses in gait with the help of means and methods of mechanics applied to the mathematical modelling.

The paper deals only with gait in the sagittal plane. In addition the next assumption is adopted: weight bearing surface is a horisontal plane. The physical model served as initial scheme for the calculation in the nine-link biokinematical chain (fig. 1)

Modern ideas about gait as a process in which not only the lower extremity take part but also the upper human body segments which exercise mutually coordinated motions are laid down as the basis for the working out of the presented model.

The purpose to make a description of different phases of gait with the help of the united system of differential equations was also kept in mind.

The motions of two lower extremities are considered simultaneously, besides that the constraints with the weight bearing surface are neglected and substituted by the ground-to-foot reactions. In such a way the well known in mechanics principle of release of constraint lets us consider the ground-to-foot reactions as the external forces applied to system.

All the human body segments located above the hip joint are modelled as a single link which in the following text will be called trunk. Each lower extremity is represented as a four--linked biokinematical chain, in addition every joint of the extremity is considered to be a roll-socket.

The equations described the motions of nine-link biokinematical chain and were composed with the following assumptions: the human body segments are absolutely rigid bodies, i.e. biokinematical chain is a system with unchanged geometric parameters, distribution of mass inside every link is even and does not depend upon the muscle tension and initial link location, that means the links have constant values of inertia moments and rigid points of centres of gravity, the constraints between the links are stationary and the whole system is holonomous.

Assumptions listed above are quite acceptable at modern level of development of gait investigations and they cannot distore substancially the obtained data.

The biokinematical chain put into motion by the moments of forces applied to the links between the joints. These moments in physical model correspond to the moments generated by the muscles in gait. Besides that the moments of friction forces are acting in the joints, but due to the lack of information about friction forces their moments are not separated from the moments of muscle forces.

The model under consideration may be used for the investigation of normal gait as well as pathological. The motions of proposed model can be described by the system of Lagrange differential equations.

One of the main problems was the determination of moments of muscle forces with the help of generalized coordinates, i.e. the second problem of dynamics should be solved.

That is why the equations were solved regarding the above moments (fig.2). To determine the moments of muscle forces out of the equations the following information should be collected: Biomechanical constants of human body, for example, the lengths and weights of different sgments with the location of their gravity centres, inertia moments and etc, inertia characteristics of single links such as "stump-prosthesis", the values of generalized coordinates or the angles between the links which can be used as generalized coordinates; components of the vector of ground-to-foot reactions and the coordinates of the point of its appliance to the foot.

The data of the first two groups are constant for all step phases according to theassumptions made, i.e. they are simple numbers.

The data from the last two groups (reaction forces, angles) are functions depending on time, i.e. they are processes.

Information needed for solution of the equations was obtained with the help of experiments and out of the analysis of published sources /2,3,4/. Investigation of dynamics of gait was carried out with the help of electronic computers (БЭСМ-4) on the basis of algorithms worked out. To aim the programmes for the computers in "algol" language were composed.

As the result of computer's processing of the initial data were obtained the charts of moments of muscle forces applied between main four joints and the values of power and energy expenditures.

In spite of the fact that information was obtained in detail these data are difficult for use in the compare analysis of different types of the prostheses. That is why it was expedient to choose as criteria of energy expenditures in gait the functionals shown below:

$$J = J\,[\,M_i(t)\,],$$

which represent the intergral indicators. In the work the following expression was determined as such criterion:

$$J_{1i} = \int_0^T |N_i(t)|\,dt\,.$$

This criterion represents mechanical work, the difference is that positive and negative works are summarized as values of similar sign.

To facilitate the comparison we come to the relative values:

$$J_{2i} = K\int_0^T |N_i(t)|\,dt\,,$$

where

$$K = \frac{T}{PL}\,.$$

This criterion is the specific energy capacity of gait. Energy losses depend only on the values of moments and time of their action - if this hypothesis is adopted, then one of the following criteria can be used:

$$J_{3i} = K\int_0^T |M_i(t)|\,dt\,,$$

$$J_{4i} = K\int_0^T [M_i(t)]^2\,dt\,.$$

We agree that static tension is also energy capacious which does not contradict to experience. The programme envisages that all the four kinds of criteria are determined. The summary criterion can be found as the sum of numerical values of criteria obtained for separate joints.

To prove that the results of investigation made with the help of mathematical modelling of gait are correct we carried out electrophysiological research which allowed to determine separately the influence of muscle forces on the gait of amputee by independent method [5].

To evaluate energy losses the information about displacement of gravity centre of the whole human body can be used. The necessary data can be obtained from the investigation of amputee gait on the prostheses of different types, besides that comparison of trajectories of gravity centres in normal and pathological walking is expedient. One of the important peculiarities of the problem under consideration is that in walking location of gravity centre inside the body changes. That means that gravity centre is not a fixed point. This fact impedes direct measurements of gravity centre displacements with the help of sensors of different kinds, for example, accelerographic sensors fixed to the subject, or, to say correctly, caused errors in the measurements made.

More accurate from the methodics point of view is the determination of phase trajectory of gravity centre by the integration of differential equations. These equations can be written as follows:

$$M\frac{d^2z}{dt^2} = R_z(t) - P\,;$$

$$M\frac{d^2x}{dt^2} = R_x(t)\,;$$

$$M\frac{d^2y}{dt^2} = R_y(t)\,;$$

where $M = P/g$ mass of human body, P – its weight;
Z,X,Y – components of gravity centre displacements: vertical, longitudinal (in dárection of ambulance) and lateral correspondingly;
R_z, R_x, R_y – components of ground-to-foot reaction.

The information about components of ground-to-foot reaction as functions of time is needed for the intergration of system /1/. Besides that the inital conditions should be defined. To find out the initial conditions periodic capacities of functions Z and Y were used. The fact that coordinate "x" changes within the step cycle "T" by value S (the length of double step) also was taken into account.

For the definition of energy characteristics of gait let us determine the whole velocity of gravity centre

$$v(t) = \sqrt{\dot{z}^2(t) + \dot{x}^2(t) + \dot{y}^2(t)} .$$

Kinematical energy changes within some period of time can be expressed by a rough inequality:

$$\Delta T \approx \frac{M}{2}[v^2(t+\Delta t) - v^2(t)] .$$

Potential energy changes in the gravity field can be written in such a way:

$$\Delta \Pi = P[z(t+\Delta t) - z(t)] .$$

The lower limit of energy losses within double step canbe found out as the sum of positive meanings of ΔT and negative meanings of $\Delta \Pi$. The proposed way gives a possibility to evaluate the energy losses in gait by simplier method. Data obtained as the result of investigations allow to carry out comparison of different types of prostheses on the basis of energy losses in gait. Mathematical model taken into consideration and experimental methods can be used in adjaicent field of science for solution of problem of locomotion.

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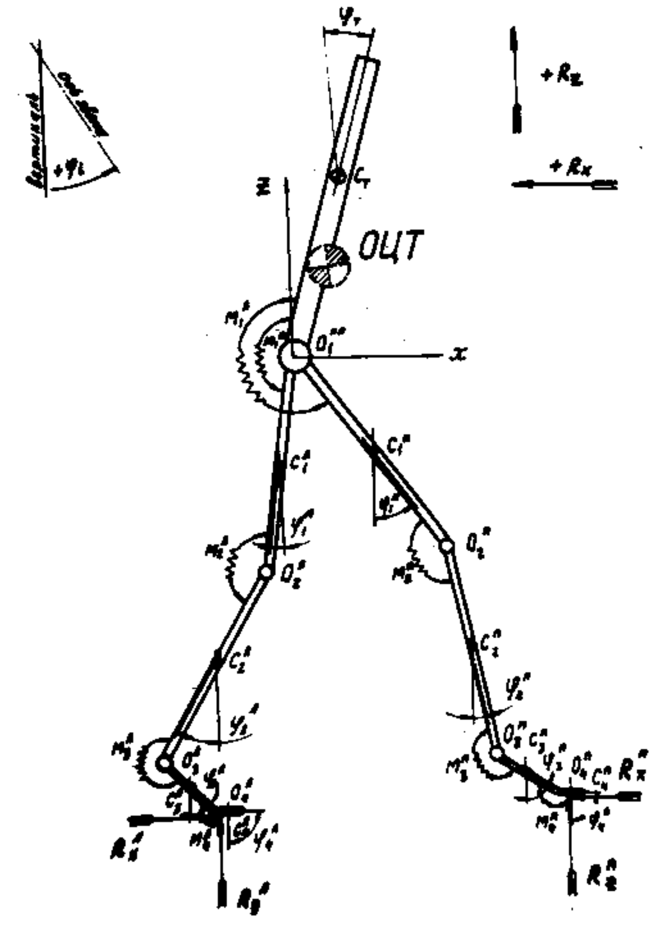

Fig. I.
Physical model of human walking.

$$M_i = M_{i+1} + \sum_{j=1}^{4} \alpha_{ji} \left[\ddot{\varphi}_j \cos(\varphi_j - \varphi_i) + \dot{\varphi}^2 \sin(\varphi_j - \varphi_i) \right] +$$

$$+ C_i \left[\ddot{x} \cos\varphi_i + (\ddot{z} + g) \sin\varphi_i \right] - \mathcal{D}_i \left(R_z \sin\varphi_i - R_x \cos\varphi_i \right)$$

$$\mathcal{D}_i = \begin{vmatrix} L_1 \\ L_2 \\ L_n \\ X^i \end{vmatrix} \qquad \begin{aligned} \alpha_{ij} = \alpha_{ji} &= \left(\frac{P_j}{g} l_j + \frac{\sum_{\kappa=j+1}^{4} P_\kappa}{g} L_j \right) L_i \\ \alpha_{ii} &= \frac{P_i}{g} \rho_i^2 + \frac{\sum_{K=i+1}^{4} P_\kappa}{g_4} L_i^2 \quad (\text{при } i < j, \kappa \leq 4) \\ C_i &= \frac{P_i}{g} l_i + \frac{\sum_{K=i+1}^{4} P_\kappa}{g} L_i \end{aligned}$$

Fig. 2.
Mathematical model of human gait

$$M_i = M_{i+1} + \sum_{j=1}^{4} \alpha_{ji}\left[\ddot{\varphi}_j \cos(\varphi_j - \varphi_i) + \dot{\varphi}^2 \sin(\varphi_j - \varphi_i)\right] +$$

$$+ C_i\left[\ddot{x}\cos\varphi_i + (\ddot{z} + g)\sin\varphi_i\right] - \mathcal{D}_i\left(R_z \sin\varphi_i - R_x \cos\varphi_i\right)$$

$$\mathcal{D}_i = \begin{vmatrix} L_1 \\ L_2 \\ L_n \\ X^i \end{vmatrix} \qquad \begin{aligned} \alpha_{ij} &= \alpha_{ji} = \left(\frac{P_j}{g} l_j + \frac{\sum_{\kappa=j+1}^{4} P_\kappa}{g} L_j\right) L_i \\ \alpha_{ii} &= \frac{P_i}{g}\rho_i^2 + \frac{\sum_{K=i+1}^{4} P_\kappa}{g_4} L_i^2 \quad (\text{при } i<j,\ \kappa \le 4) \\ C_i &= \frac{P_i}{g} l_i + \frac{\sum_{K=i+1}^{4} P_\kappa}{g} L_i \end{aligned}$$

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Mathematical model of human gait