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INFLUENCE OF PROSTHESIS PARAMETERS ON ENERGY LOSSES OF THE INVALID IN WALKING

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Abstract

Advance in mathematical modelling of human normal and pathological gait as well as expanding of computers utilization in biomechanical research give a chance to study the problem of the optimization of choice of the prosthetic parameters on the basis of some criteria.

One of the generally used criterion is the energy expenditure in gait. The mathematical model of gait of the amputee with lower extremity prostheses is developed.

It permits to determine the trajectory of the centre of gravity of the human body and the energy expenditure in walking as functions of the location parameters of prostheses links and human body segments.

The equations and programmes for computer are worked out on the basis of the above approaches. It is envisaged to compare the computerized data with those obtained by the ingenious techniques which is used in the experiments with the invalids wearing prostheses with alignment and balance units.

Introduction

Method of optimisation of above-the-knee-prosthesis parameter selection based on the power criteria is described. The energy losses of the invalid in walking are determined by his weight and the trajectory of body gravity centre which depends on the mutual position of body and prosthesis, inertia and geometry characteristics of the prosthesis and also on the kinematic properties of the links. Evaluation of the relative importance of the prosthesis parameter variations for the changes in energy losses of the invalid on different phases of step is suggested.

As the result of progress in the creation of mathematical models for the description of normal gait as well as this of a man on prosthesis, and due to the wider employment of computers the task of optimal choice of the lower extremity prosthesis according to definite criteria became on of the prime tasks. One of the general criteria is evidently the energy cost of gait of an invalid on a prosthesis. The energy losses of the invalid in walking depend on the parameters of the interlocation of body and prosthesis parts, inertia and geometry characteristics of the prosthesis, as well as kinematic properties of its links. Deviations of the prosthesis parameters from the optimal, hamper the prosthesis control and lead to the growth of energy losses. Energy losses of the invalid in gait may be evaluated by measuring the interchange of gasses or by the electric activity of muscles. But these two methods do not permit usto find analytical relations between energy losses and prosthesis parameters, which is necessary on order to solve the problem of prosthesis parameter selection without carrying out a great number of tiring experiments.

Application of the mathematical model of invalid's gait makes it possible to remodel different combinations of the prosthesis parameters with the aim of optimization. The simpliest analytical relation exists between the energy losses for the shifts of the body gravity centre and parameters of the body segments and prosthesis links. The trajectory of the gravity centre during normal walking is a complex spacial curve. The trajectory of the gravity centre of an invalid with an above-the-knee-prosthesis will be scrutinized as a result of some perturbating influence on the trajectory of the gravity centre in normal walking.

First we shall see what parameters determine the movements of the body gravity centre. In biomechanics the human body in locomotion is usually presented as a multi-linked ramified biokinematical chain. Motion of body segment and prosthesis links in walking may be characterized by their angle deviations from the vertical line. Motion of segments and links, their masses, static radii and lengths determine the trajectory of body gravity centre in walking. For n-link mathematical model of normal gait describing the motion of human body in saggittal plane, accelerations of the gravity centre motion in fore-and-aft and vertical directions are determined with the help of the following equations:

$$\ddot{z}_c = -\frac{1}{M}\Big[\sum_{i=1}^{n} m_i s_i \left(\ddot{\varphi}_i \sin\varphi_i + \dot{\varphi}_i^2 \cos\varphi_i\right) + \sum_{i=1}^{n} \ell_i \left(\ddot{\varphi}_i \sin\varphi_i + \dot{\varphi}_i^2 \cos\varphi_i\right) \sum_{j=i+1}^{n} m_j\Big], \quad (1)$$

$$\ddot{x}_c = -\frac{1}{M}\Big[\sum_{i=1}^{n} m_i s_i \left(-\ddot{\varphi}_i \cos\varphi_i + \dot{\varphi}_i^2 \sin\varphi_i\right) + \sum_{i=1}^{n} \ell_i \left(-\ddot{\varphi}_i \cos\varphi_i + \dot{\varphi}_i^2 \sin\varphi_i\right) \sum_{j=i+1}^{n} m_j\Big], \quad (2)$$

where m_i, s_i, ℓ_i are mass, static radius and length of the n^{th} link, $\varphi_i, \dot{\varphi}_i, \ddot{\varphi}_i$ are angle deviations, velocities and accelerations of the n^{th} link from the vertical axis.
M is the human body mass.

In the similar way for walking with the above-the-knee-prosthesis we may write equations which will include some parameters of the prosthesis construction scheme. In their usual form equation (1), (2) may be presented as follows:

$$\ddot{z}_c = F_z(m_i, s_i, \ell_i, \varphi_i, \dot{\varphi}_i, \ddot{\varphi}_i, u, v), \quad (3)$$

$$\ddot{x}_c = F_x(m_i, s_i, \ell_i, \varphi_i, \dot{\varphi}_i, \dot{\varphi}_i, u, v), \quad (4)$$

where "u" and "v" are parameters of the prosthesis construction scheme, for example frontal shift of the socket and its inclination angle.

Equations (3) and (4) are Newton's equations describing the dynamics of a single particle. Quantities F_z and F_x are components of the force acting on the particle.

Let us consider that equations (3), (4) describe the motion of gravity centre in normal walking. Alongside with nonperturbated motion (in normal walk) of the gravity centre we shall study the perturbated motion (in walk with prostheses). It also may be treated as gravity centre motion caused by some force close to F :

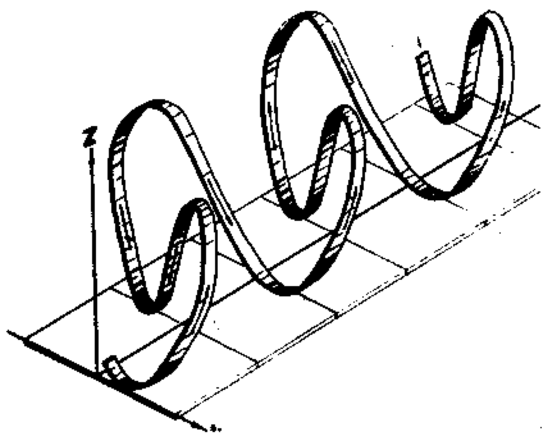

Fig. I. Trajectory of human body's centre of gravity in normal walk.

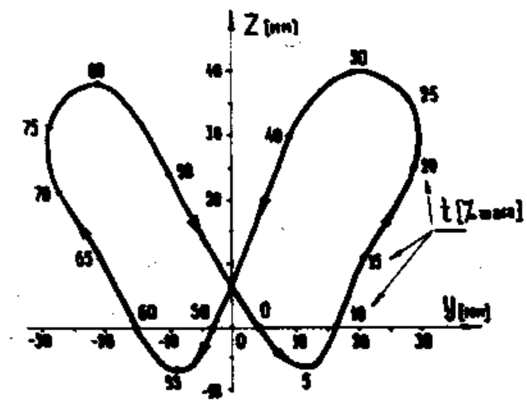

Fig. 2. Trajectory of human body's centre of gravity in frontal plane.

$$\ddot{z}_c^* = F_z^*(q_j^i), \qquad (5)$$

$$\ddot{x}_c^* = F_x^*(q_j^i), \qquad (6)$$

where q_j^i parameter of biokinematical chain, j represents number of parameter, $i=1,\dots n$ is the number of the link of biokinematical chain.

Suppose that F^* differs slightly from F, then we may say that differences between perturbated and nonperturbated motion is conditioned first by the changing of initial conditions, second by the changing of the equations (3), (4).

As an example take the vertical displacements of gravity centre in normal walk and that with above-the-knee prosthesis Initial values in normal walk, when $t=t_0$ may be represented as

$$z_c = f_c^0(0, C_1, C_2) = z_c(0) \quad \text{where} \quad C_i = const \quad (i=1,2).$$

Let us include the differential equation

$$\ddot{z}_c^* = F_z(q_j^i) + \mu\Phi(q_j^i) \qquad (7)$$

where μ is small parameter, $\Phi(q_j^i)$ is some function of the parameters.

Perturbated motion will be represented by the solution of the equation (7) which satisfies the initial conditions when $t=t_0$: $z_c^* = f_c^0 + \alpha_c^0$ where α_c^0 is a very small value called the initial perturbation.

Introduce instead of z_c^* perturbation $\alpha_c = f_c - z_c^*$ and we can write the following:

$$\ddot{\alpha}_c = F_z(q_j^i + \delta q_j^i) - F_z(q_j^i) + \mu\Phi(q_j^i). \qquad (8)$$

Let us take the supposed extremely small perturbation for limited period of time $t_0 \le t \le T$ where T is the duration of double step. For the exact equation (8) we substitute its expansion. Then ignoring the members of higher degree of smallness we come to the equation:

$$\ddot{\alpha}_c = \sum_{i=1}^{n}\sum_{j=1}^{k}\left(\frac{\partial F_z}{\partial q_j^i}\right)_0 \delta q_j^i + \mu\Phi(q_j^i). \qquad (9)$$

Index "O" indicates that expressions q_j^i for normal walk should be substituted into the formulae under consideration. Coefficients $\frac{\partial F_z}{\partial q_j^i}$ form a rectangular matrix, which reflects the value of the influenc of each biomechanic parameter variation on the quantity of gravity centre motion perturbation. For example coefficient $\partial F_z/\partial m_i$ (for parameter q_j^i is taken the mass of i^{th} link) is found according to the following formula

$$\frac{\partial F_z}{\partial m_i} = -\frac{1}{M}s_i(\ddot{\varphi}_i \sin\varphi_i + \dot{\varphi}_i^2\cos\varphi_i) + \frac{1}{M^2}\Big[\sum_{j=1}^{n} m_j s_j(\ddot{\varphi}_j \sin\varphi_j + \dot{\varphi}_j^2\cos\varphi_j) + \sum_{j=1}^{i} \ell_j(\ddot{\varphi}_j \sin\varphi_j + \dot{\varphi}_j^2\cos\varphi_j)\sum_{k=j+1}^{n} m_k \qquad (10)$$

Modelling of the $\partial F_z/\partial q_i$ coefficients with the help of computers showed that some of them have impulse character as in relatively short time periods they change more than for an order.

When determining the influence of the biomechanical parameter variations on the energy losses of invalid we proceded from the following formula for the determination of energy losses E for motion of gravity centre:

$$E = \int_0^T |(\vec{P} + M\ddot{\vec{z}}_c)\cdot\dot{\vec{z}}_c\, dt \qquad (11)$$

where P is the weight of the invalid,
$\vec{r}_c$ is radius-vector of the gravity centre of the invalid for a fixed coordinate system.

It is interesting to determine the influence of the body and prosthesis links mutual position on the energy losses in walk and to compare theoretical and experimental data. During the experiment only one parameter of the prosthesis x_2 (frontal displacement of the socket in lateral or medial direction) was changed with the help of an ajustment unit when all the other parameters and the socket were the same. Registration of gravity centre displacements was carried out with $x_2 = 20$ mm which corresponds to the converge scheme adopted by CNIIPP* and with $x_2 = -20$mm, which corresponds to the diverge scheme.

As it became clear from the analysis of the theoretical and experimental data, the energy losses of an invalid with a prostheses of converge scheme is by 28j per step less than with the prosthesis of diverge scheme under condition that tempo of walk does not change.

Thus we come to the conclusion that analysis of body gravity centre motion in normal walk and in walk on prosthesis, the study of the influence of biomechanical properties of the prosthesis on the value of deviation from the normal walk may give us important information which is useful for designing of above-the-knee-prostheses, especially for prostheses with external power sources.

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