A POSSIBILITY OF CONTROLLING THE HUMAN LOWER-EXTREMITY PROSTHESIS

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Introduction

One of the basic difficulties encountered in the realization of the prostheses, the performances of which would widely surpass the accomplishments so far achieved with respect to the functionality, adaptivity, variety and spontaneousness of movements, is that such prostheses in principle call for a greater number of independently but coordinately externally controlled points. This requirement conditions the solving of two complex problems: the problem of power supply for a greater number of driving motors, and the problem of coordinate control of all driving points by the patient. Having the second problem in mind in the case of bilateral prostheses for human lower-extremities, a solution of control system is proposed in this paper.

In working out the concept of this control system it has been the aim to enable the following:

— control of leg prostheses with as much variety and freedom of movements as possible,

— control adaptivity depending on conditions under which the movement is realized,

— spontaneousness of movements,

— patient's perception of the movement he is carrying out and of the ambient in which it is done, and, consequently,

— feeling of stability.

By the mentioned characteristics of the control system the function of the prostheses would be considerably increased. The control principle which will be presented can be applied both to bilateral or unilateral leg prostheses and to bilateral or unilateral orthoses.

Basic Concept of Controlling Human Lower-Extremity Prosthesis

The movements of legs and thereby the stable locomotion of a person is realized by coordinate changes in five angles of each leg, that in the schematic illustration of the human body (Fig. 1) are designated by α_{ij} (i=1,2; j=1,2,3,4,5). In fact, as it is already known, human lower-extremities have a greater number of freedom degrees than those considered here, but it can be easily recognized that by coordinate control of the marked angles, a sufficiently great variety in positions and movements of particular parts of the legs can be achieved in order to realize all the basic postures and types of motion.

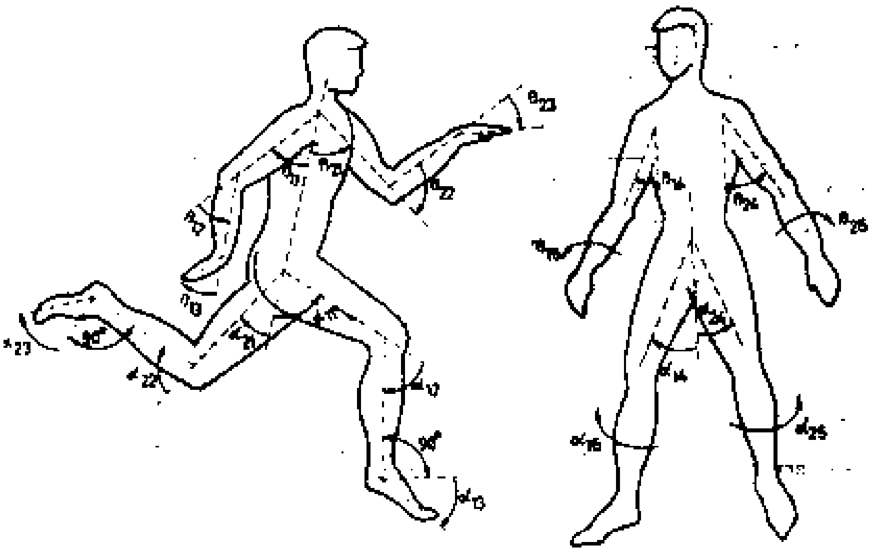

Figure 1. Schematic diagram of the human body

On the other hand, human upper extremities (hands are considered as unique entities) as former organs for locomotion, have the same number of basic freedom degrees, that is, with each arm there also exist five basic angles that can independently be changed in sufficiently wide limits. These angles in the schematic diagram of the human body (Fig. 1) are marked by β_{ij} (i=1,2; j=1,2,3,4,5), whereas for intercorrespondent angles of upper and lower-extremities the same indices are adopted.

Immediately, an idea occurs that in the case of a patient with bilateral leg prosthesis and healthy upper-extremities, the prosthesis control could be done by movements of the upper extremities. Taking into account the natural intercorrespondence of partificular parts of the human upper and lower-extremities, i.e., angles β_{ij} and α_{ij}, the control of leg prostheses could be achieved by ten independent automatic control systems that would transfer the angles β_{ij} of arms on the correspondent angles α_{ij} of the leg prostheses through appropriate functional dependences:

$$\alpha_{ij} = F_i(\beta_{ij}), \qquad i=1,2;\ j=1,2,3,4,5. \quad . \quad . \quad . \quad . \quad . \quad 1$$

From the point of view of the patient's training and technical realization of the system, the linear relations between intercorrespondent angles would probably be the most convenient so that we would have:

$$\alpha_{ij} = K_j \cdot \beta_{ij},$$
$$K_j = \text{const.} \qquad i=1,2;\ j=1,2,3,4,5. \quad . \ . \ . \ . \quad 2$$

In this way, according to the exposed basic concept, the entire control system of the bilateral leg prosthesis would consist of ten independent position servosystems whose block diagram is shown in Figure 2, together with the patient himself, that is, his nervous system which is assigned for intercoordination of the operations of these servosystems.

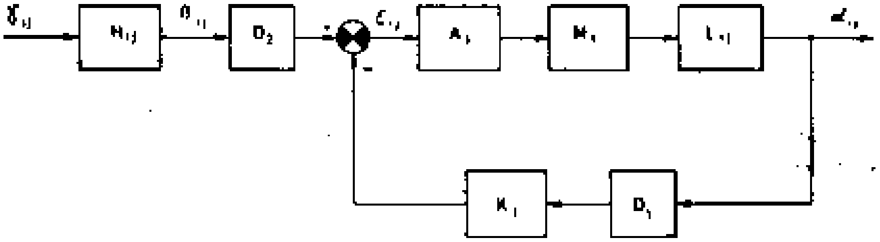

Figure 2. Block diagram of one of the ten independent servosystems. H_{ij} — part of arm, L_{ij} — corresponding part of leg prosthesis, A_i — servoamplifier, M_i — servomotor with self-locking device, K_j — adjustable feedback gain, D_1 and D_2 — devices for angle measurement, γ_{ij} — muscle force, β_{ij} — angular position of the part of arm, α_{ij} — angular position of the corresponding part of leg prosthesis, ε_{ij} — error signal

Though this is obvious, let us note that with the assumed directions of the changes in angles as indicated in Figure 1, the movements would be very similar to the natural ones for a series of typical motions.

Artificial Sensory Feedback System

In the suggested concept of controlling the prostheses of human lower-extremites it is foreseen that the intercoordination of the motions of particular parts of the prosthesis would be done by the patient himself who will, in doing this, use his nervous system for making decisions, maintaining the balance and the stability of motion. However, as it is known, a healthy man coordinates his movements correctly because his sensory feedback system trough his nervous system is continuously informed about the instantaneous state and dynamics of the motion he is carrying out, as well as about the ambient and conditions under which he realizes them. By the proposed control system no information paths from the prostheses to the patient's nervous system has been realized which would replace his destroyed part of the sensory feedback system. It is true that in the stationary state the patient would have a certain sense about the positions of the leg prostheses on the basis of the positions of his arms, but due to inertial delays in transient states, he would lose all information on instantaneous position and dynamics of the prostheses motions. Also, there is pa possibility of visually following the motions of the prostheses and visual collection of data on the vicinity, but therewith the patient still does not obtain either quantitativaly or qualitatively sufficient information in order to be able to control his locomotions successfully. In order to reduce this disadvantage and to enable the patient to control the motions of the prostheses coordinately, an artificial sensory feedback system is provided.

The principle of the artificial sensory feedback system is in the mechanical forces δ_{ij} $(i=1,2;\ j=1,2,3,4,5)$ which are generated proportionally to the errors of position servosystems.

$$\delta_{ij} = C_j \cdot \varepsilon_{ij}, \qquad C_j = \text{const.} \qquad i=1,2;\ j=1,2,3,4,5. \quad \ldots \quad 3$$

These mechanical forces affect the corresponding parts of arms H_{ij}, so that they tend to move them in the direction of reducing the errors ε_{ij} as shown in the block diagram of one out of ten independent servosystem (Fig. 3). Constants C_{ij} would be adjusted so that the patient can overcome the mechanical forces δ_{ij} without great effort by his muscles forces γ_{ij} and move particular parts of his arms only if the errors on position servosystems ε_{ij} are within allowable limits.

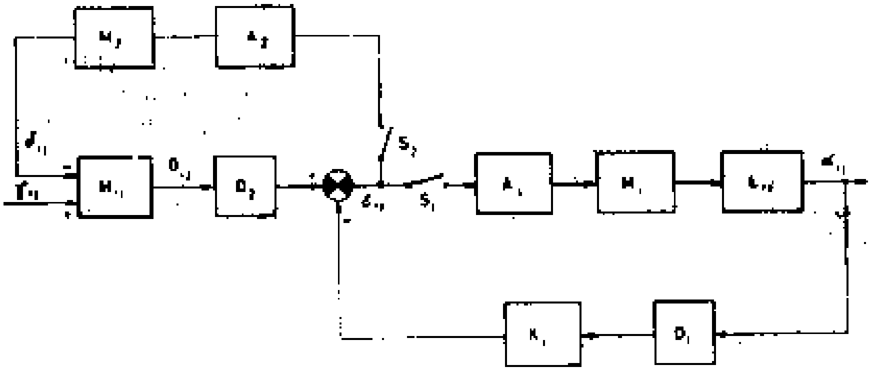

Figure 3. Block diagram of one of the ten independent servosystems with artificial sensory feedback. H_{ij} — part of arm, L_{ij} — corresponding part of leg prosthesis, A_1 and A_2 — servoamplifiers, M_1 — servomotor with self-locking device, M_2 — servomotor without self-locking device, K_j — adjustable feedback gain, D_1 and D_2 — devices for angle measuring, S_1 and S_2 — switches, γ_{ij} — muscle force, δ_{ij} — mechanical force, β_{ij} — angular position of the part of arm, α_{ij} — angular position of the corresponding part of leg prosthesis, ε_{ij} — error signal

Now we can explain the operation of the entire control system. Let us suppose that the leg prostheses are in the state α°_{ij} $(i=1,2;\ j=1,2,3,4,5)$ and that the system is in a steady equilibrium, that is, the angles of the leg prostheses correspond to the angles of arms:

$$\alpha_{ij} = K_j \cdot \beta^{\circ}_{ij}, \qquad i=1,2;\ j=1,2,3,4,5. \quad \ldots \quad 4$$

Let us suppose also that the patient wants to transfer the prostheses from the state α°_{ij} into the state α^{1}_{ij}. To do this he must, by his muscles force y_{ij}, move the parts of his arms H_{ij} into the appropriate position β^{1}_{ij}. However, immediately after he moves the arms from the state β°_{ij}, due to inertial delays of the prostheses errors appear on position servosystems and therefore mechanical forces δ_{ij}, too. These mechanical forces counteract the muscle forces tending to bring the arms back into the position that would correspond to the instantaneous position of the prostheses. Since the patient, by the force of his muscles, can overcome the mechanical forces when errors ε_{ij} are within permissible limits, he can transfer the leg prostheses from state α°_{ij} into the state α^{1}_{ij} only by moving the arms sufficiently slowly, and working against the mechanical forces. Any rapid movement of the arms will be stopped.

The importance and goal of the artifical sensory feedback system is manifold:

— the patient has a perception of the dynamics by which the leg prostheses follow the movements of his arms,

— the patient senses the accuracy by which he has realized a particular position,

— accidental or rapid movements of arms, which could lead to undesired displacement of leg prostheses and eventual loss of balance, are impossibile,

— the patient senses any obstruction encountered in his motions by any part of the prostheses,

— the patient can assess whether the ground onto which he puts his leg prostheses is firm or not, slippery or rough, and the like,

— the patient can regulate the pressure of the prostheses upon the ground in permissible limits.

Taking into account all the mentioned qualities of the artificial sensory feedback system, the training of the patient would not be difficult, he could successfully coordinate the motions of particular parts of the prostheses and realize a stable locomotion.

Operation Regimes of Prostheses

For a patient using the prostheses with the described control system, there would exist three possible regimes:

a) regime of work or rest,
b) automatic preparation for locomotion, and
c) regime of locomotion.

Regime of Work or Rest. When the patient wants to do something with his arms or have a rest, he would, by using the described control system, come to a steady equilibrium position that may be in standing or sitting pose. By switching out the switches S_1 and S_2 (Fig. 3), the patient stops both the operation of the driving servosystems and the functioning of the artificial sensory feedback system. Afterwards, he can move the arms freely not causing any displacements of the leg prostheses. He carries out the desired work or he rests. In order to avoid the undesired movements of arms for manipulating the switches S_1 and S_2 they would be placed on the hand so that the patient can manipulate them only by moving his fingers.

Automatic Preparation for Locomotion. In order to reach the regime of locomotion it is previously necessary to accomplish a preparation; at the moment of passing to the regime of locomotion, that is when the switch S_1 is switched on, angles of arms β_{ij} must correspond to the instrantaneous angles of leg prostheses α_{ij} . Contrarily, at that moment there could appear abrupt and undesired motions of the leg prostheses, loss of balance and fall. This preparation is done automatically. The patient switches on only the switch S_2 while switch S_1 remains open. Since thereby the driving servosystems are still out of work, the leg prostheses do not move and the artificial sensory feedback system, which is now switched on, brings the patient's arms into the position that corresponds to the instantaneous position of the leg prostheses.

Regime of Locomotion. After the preparation has been done, by switching in the switch S_1, too, the system passes into the regime of locomotion. The desired locomotion is accomplished by the patient by slow coordinated movements of arms in the way already described. It is clear that in the regime of locomotion his arms are exclusively engaged for controlling the desired motions and he cannot do any other work with his arms at the same moment.

Conclusion. The paper deals with a system for controlling the human lower-extremities prostheses. The principle of this system is in ten servosystems which transfer the movements of arms and convert them into the movements of leg prostheses. For intercorrespondent angles of arm and leg prostheses those angles have been adopted which give as much spontaneous motions as possible. The coordination of servosystems operations is done by the patient himself. In order to enable him to do this, an artificial sensory feedback system is foreseen. This system gives the patient the sense of instantaneous state and the dynamics of movements he is carrying out, as well as of the ambient and conditions under which he is doing them.

An easy and automatic transfer from the regime of work into the regime of locomotion and vice versa enables the patient to use his arms successively for work and control of locomotion. The whole system can be realized by standard technique. The exposed principle of control can be used for complete or partial, bilateral or unilateral prostheses or orthoses of human lower-extremities.