HYBRID ACTUATORS FOR ORTHOTIC SYSTEMS
HYBRID ASSISTIVE SYSTEMS

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Introduction

A high proportion of the total population of patients in need of assistive devices suffers from neuromuscular insufficiencies. Amputees of all kinds are only a small part of the total number og handicapped persons. According to statistics the number of persons in U.S.A. in need of braces amounted to about 3,400.000 in 1969. The number of amputees for the same period was only 300.000.

The loss of motor activity due to neuromuscular damage manifests itself in very different ways. In many instances the control of motor activity is not completely lost, but only reduced to some extent. In addition, internal (biological) power sources are also available, although not always at the energy level needed for the dynamic of normal skeletal activity.

The rehabilitytion of persons suffering from neuromuscular insufficiencies has followed so far two main lines. Assistive devices, passive or active, were attached to the human skeleton in order to reproduce the desired mechanical trajectories and mechanical tasks. If, however, some muscles are available as actuators but the control is lost, then external supply of missing signals is the natural solution. In such cases Functional Electrical Stimulation of Extremities (FESE) is applied in order to bypass the damaged part of the biological control signal path.

In this paper a third approach to the rehabilitation of patients with neuromuscular insufficiencies is proposed. It is based on simultaneous (parallel) application of FESE and of externally powered assistive devices. Therefore the name hybrid method is proposed. Before describing the philosophy of hybrid assistive systems a brief review of the relevant features of the powered orthoses and FESE will be given.

Functional Electrical Stimulation of Extremities

The great advantage of the FESE approach is the direct use of available biological actuators and available internal power.

Thus the hardware part os assistive system is simplified since external powered actuators are not needed, the interface for the transfer of external forces to the human skeleton is not required. The technology is essentially used only for the transfer of control signals between the man and the machine.

Practical application of this method runs into great difficulties. First of all, the transmission of external signals to the most efficient control point within the muscular tissue is not straightforward. Cutaneous and percutaneous electrodes used for signal transmission have serious disadvantages. Implanted electrodes have been recently used for that purpose /1/.

The difficulties with FESE are limited not only to the transmission of control signals. The inherent assumption for the successful implementation of FESE are following:

1. The actuator (muscle) should behave as a completely controllable time-invariant plant.
   This is evidently not the case since fatigues, reflex activities and response variations, due to variable geometry between electrodes and excitable tissue, change the transfer function of the biological actuator in unpredictable ways.
2. In more severe deficiencies of the locomotor system FESE must be applied to several joints. Thus, a system of time-varying plants with partially predictive behaviour must be controlled. A definite coordination pattern depending on the desired locomotor function must be imposed upon the system. This fact explains why practical use of FESE has been limited essentially to one degree of freedom.
3. It is assumed that there is sufficient internal energy left over to perform mechanical tasks with acceptable dynamics. As known, this is not always true.

From the above considerations it becomes clear why FESE cannot be taken as a general solution for locomotor deficiencies in paralyzed or paretic patients.

Active Orthoses

Active orthotic devices have been used in order to restore the lost control of upper and lower limbs. In principle, external control may be applied equally to one or several joints simultaneously. However, the multijoint external control of human extremities is a complex task. It requires extensive theoretical and practical studies of interdisciplinary nature. As a theoretical approach, multilevel control with specific optimization criteria has been proposed for the design of multivariable mechanical and skeletal systems /2,3/.

The name exoskeleton has been used in conjunction with complete external multijoint control of biped locomotion. Such an active orthotic device is intented to assist paralyzed or paretic patients. The design principles of active exoskeleton devices have been studied by M. Vukobratović /2,4/.

The objective of the exoskeleton method is to assist patients with severe deficiencies of the locomotor system. Thus, for example, paraplegic patients using the wheelchair are considered as potential candidates of the exoskeleton type assistive device. The actual state of this research is quite promising although great efforts must still be made before practical results will become available for rehabilitytion purposes.

The exoskeleton approach covers in principle a wide class of patients with deficiencies of the locomotor system. On the other side, it has its own disadvantages:

(1) The total amount of energy for motion must be supplied externally. Therefore, the patient is only partially autonomous with respect to the external power supply.

(2) The exoskeleton is in contact with large parts of the body so that the complex space-time force patterns are transferred to the human skeleton. Consequently, the interface problem becomes quite complex.

(3) The stability of the exoskeleton system even when using quadrupedal gait (two canes) is smaller than the displacement with the wheelchair.

The above remarks about FESE and the active orthoses are not intended to reduce the value of each method when applied independently. For the large variety of patients with locomotor deficiencies there does not exist a general and "best" solution. Rehabilitation specialists should have at their disposal a wide range of technological solutions which they can use according to the needs of the patient. Being aware of this fact the authors have initiated some preliminary studies in order to develop a new rehabilitation approach combining the advantages of both FESE and the exoskeleton /5/.

The Hybrid Actuator

In general, several forces act upon a joint of an orthotic system:

- Muscle force still under voluntary control as in paretic muscle or in cases where e.g. the agonist is under voluntary control and the antagonist is paralyzed.
- Force obtained through voluntary activation of another nonparalyzed muscle (body powered orthosis).
- Forces from passive energy sources (elasticity, inertia, gravity).
- Reactive forces due to mechanical fixation and stabilization of the joint.
- Forces from active energy sources such as electrical, pneumatic, and hydraulic motors (externally powered orthoses).
- Forces due to electrical stimulation of the paralyzed or paretic neuromuscular system.

In order to simplify the orthosis, to save energy, or to obtain better performance, in practically every orthosis a combination of the above forces is acting on the joint. An orthotic actuator which achieves functional movements by a (usually sequential) combination of several forces is defined as a combined actuator. Several types of combined actuators have been proposed for rehabilitation purposes /6,7,8,9,10,11/.

In contrast to these relatively simple combined actuators, all of which operate essentially as open-loop systems with trivial energy-mode switching characteristics, we should like to propose a new combined actuator which has the following properties:

(1) It should combine biological and external energy sources to obtain a prescribed functional movement.

(2) The sequence of introducing the energy sources has to follow a hierarchical concept where:
   - first, voluntary effort has to be exploited to a reasonable maximum,
   - second, electrical stimulation is added until a reasonable limit is reached (e.g. pain),
   - third, external power is added if the first two energy sources are inadequate to obtain the desired movement.

(3) The actuator has to have engineering feedback loops which

will control the available energy sources in an optimal way depending on the specific performance criteria.

Due to the intricate interaction of the electrical stimulation control loop and the control loop of the external power source which have to work in parallel, we propose that an actuator with the above properties be defined as a hybrid actuator.

In the definition of the hybrid actuator there is inherently built-in a large flexibility in operating conditions. Therefore we belive that this actuator presents one of the most general solutions to the problem of joint - movements in orthotics.

In Figure 1 a block diagram of the hybrid actuator is shown. The musculo-skeletal joint is mechanically connected with an external splint. M_1 and M_2 are are biological motors (stimulated muscles) and M_3 is an externally powered motor. At least two components of the output vector $\overline{x}$ have to be measured: the joint angle $\overline{\phi}$ and the interacting force F which appears between the splint structure and the extremity.

Let us assume that the muscle are completely paralyzed (no voluntary control) and that no spontaneousy reflex activity is present (e.g. spasticity). A typical example of hybrid operation would then be the following /12/. For small control vectors, u, the stimulation control-loop $C_1 - C_3 - M_1, M_2 - \overline{\phi} - \overline{x} - \overline{e}$ would be working and another loop $C_1 - C_2 - M_3 - F - \overline{x} - \overline{e}$ would move the mechanical splint in such a way that F would be minimized. If the dynamic or static requirements of u exceed the capabilities of the stimulation loop the circuit will switch to a primary activity of the external motor loop ($C_1 - C_2 - M_3 - \overline{\phi} - \overline{x} - \overline{e}$) and the stimulation loop would be reduced to a supporting role. The basic principle of the hybrid assistive method is thus to support FESE in the case when for some reason the biological actuators fail to follow the prescribed trajectory or the biological power supply can not meet the dynamic requirements.

From a control engineering viewpoint the most important question is to find bioengineering performance criteria for optimal load sharing between the biological and the external servomechanism. The task is not easy since a mechanical system with deterministic stationary transfer function operates in parallel with the biological servo having non-stationary, non-deterministic characteristics.

Factor of Hybridization

According to our definition of a hybrid actuator, three forces contribute to the resulting force F, which is maximally required to achieve a functional movement. F_1 is obtained with voluntary effort, F_2 with electrical stimulation, and F_3 with external motors.

$$F = \sum_{i=1}^{3} F_i.$$

Let us introduce weighting factors

$w_1 = F_1/F$, $w_2 = F_2/F$ and $w_3 = F_3/F$.

Therefore

$$\sum_{i=1}^{3} w_i = 1.$$

The three extreme cases are: $w_1 = 1$ (normal subject), $w_2 = 1$ (ideal candidate for FESE) and $w_3 = 1$ (completely paralyzed and atrofied muscle).

The amount of hybridization could thus be defined by a vector

$$w = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix}$$

where all cases with $w_i = 1$ represent trivial situations with no hybridisation at all.

Another way of looking at the problem of hybridization is the following. Suppose we want to express mathematically the amount of mixing or interaction of the available power sources. If this interaction is maximal the factor of hybridization, h, should be maximal. On the other hand, if only one of the power sources would activate the joint, h should be zero, since there is no hybridization. A function which is maximal if all w_i are equal and becomes zero if any $w_i = 1$ is very well known from information theory:

$$h = \sum w_i \log w_i$$

According to this definition the factor of hybridization does not give an insight into the contributions of various energy sources to the desired dynamics or force, but it definitely is a measure of the complexity of interaction of the different sources.

Conclusion

A new approach to the design of assistive device for patients suffering from neuromuscular insufficiencies has been proposed. The potential field of application of hybrid actuators are those cases where neither FESE nor active orthoses can be considered as optimal solution.

New types of assistive devices are needed keeping in view the great variety of neuromuscular insufficiencies. In this way it will be possible to combine active, passive, and hybrid joints into a complex assistive system in order to best suit the specific needs of the patient. The design of the satisfactory hybrid actuator remains thus the main problem so that it can be used as a reliable unit of the complex assistive system for the patient. Such a modular approach (using units of different nature to meet the needs of the patient) is feasible to-day since enough knowledge about FESE and design of antropomorphic robots is available.

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