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HYBRID ORTHOSES FOR DEFICIENT LOCOMOTION

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SUMMARY - This paper describes the synthesis of the hybrid orthosis model and its applications. The hybrid orthosis (HO) model is based on the self-fitting modular orthosis (SFMO), on functional electrostimulation (FES), using non-numerical control (NNC) and artificial intelligence methodology. The motif of this paper is the possibility of parallel activation of biological actuators (muscles) and the external sensitive system by using artificial reflex arcs control (ARAC) for synthesising functional movements that perform locomotion.

INTRODUCTION

There are two approaches to the synthesis of assistive systems (orthoses) for upright locomotion. The mechanicistic approach focuses on the development of external anthropomorphous skeletons, while the neurophysiological approach favors the use of functional electrostimulation. The anthropomorphous mechanisms have been greately improved by the advances in robotics methodology (Rabishonge, 1975, Vukobratović, 1978; Popović 1978). The generalization of biomechanical models (Popović 1980) comprises the duality of the egzoskeleton - human body operation, and soft orthosis-man interface. The principles of complete external energy providing functional movements, and of three-point fixation have been abandoned. Control based on dynamics studies has been improved (adaptive control- - Vukobratović, 1982) as well as the nonnumerical approach (logical control - - Tomović, 1981) that has evolved into control based on AI methodology. Therefore, real-time control, compatible with biological control, is possible. Functional electrostimulation also provides for some forms of locomotion due to new insights in neurophysiology and the technical-technological advancements (Kralj, 1980; Riso, 1983; Marsolais 1984; Kralj, 1984). Wider use of FES was made possible by multichannel stimulation.

The indication area for HO treat ment is defined by the pathological substratum that caused a specific type of locomotion insuficiency, and by the features of chosen substitution elements.

The described HO concept has the ability to combine elements of three different systems: SFMO, FES, and CA whose indication areas for individual use have already been practically verified. In order to justify the combination of two or more systems, it should result not only with an acceptable and more advanced level of locomotion for certain pathological conditions but also with a wider indication area for patient categories whose treatment with a selected system produced no substartial results.

It is necessary to define criteria and conditions for each pathological condition that should be fulfilled before bracing can begin, and to systematize indications by the principle of favourable outcome probability for HO treatment. Also it is necessary to predict possible positive and negative influences on the HO treatment.

The control strategy constitutes an important part of this biomechanical system. The duality of performance necessitates compatibility among the energetic aspect and the control aspect while at the same time, technical reasons limit energy consumption and force transfer from environment to man. Bionic sensors have an important role, considering that a large number of input informations increases the compatibility of the system.

I HYBRID ORTHOSIS - A BIOMECHANICAL MODEL

It has already been mentioned that the HO was the logical success to the development of egzoskeletal type orthoses and functional electrostimulation applications. The biomechanical model for the HO is a simplified model of the man (an anthropomorphous mechanism) (Fig. 1), whose segments have variable mass and length, and are linked to the self-fitting modular orthosis with cybernetic actuators, by highly elastic interfaces (Popović, 1983). Simplifications on the human model have no impact on the generality of the study, because the model is used for observation of the so called muscle equivalent features. In fact the muscle equivalent performance is reduced to action activities (Fidelius, 1971). Here, we observe only one module (the complete man-orthosis system has been analyzed equivalently by Davidović and Popović in 1984) in order to explain its functioning.

The system model is composed of bionic sensors, a microcontroller, and of SFMO moduls. One of the possible locomotoion actions (standing up, walking, sitting down, getting up, turning around etc.) is chosen voluntarily by the patient. This choice, via AI method, conveys a series of discrete state vectors to the microcontroller, that correspond to certain phases of activity. Movement control of functionally disabled extremities (according to the adopted strategy) is exerted either by single channel or multichannel stimulation, using surface, subcutaneous or implanted electrodes. However, if the external effect on the muscles does not produce the desired movement (spasms, muscle exhaustion, lesion of the motor neuron or the muscle itself), which is registered by bionic sensors of the controller i.e., by comparing the state vector of the system (set of data given by BS) with the discrete (preset) state vector (storred in the memory of the MC), the cybernetic actuator provides equivalent muscle effect via the highly elastic interfaces. The acting of the external skeleton i.e., the locking device in the scope of the CA) is used for static phases of locomotion.

The mathematical-mechanical model of the system is analyzed on the computer. The form of the adopted system suited to stimulation demands is described by the matrix equation:

$$|\alpha||\ddot{q}| + |\beta||\dot{q}| + |\gamma||q| + |\delta||\omega| + |F^*| = 0$$

or in the Cauchy form

$$\frac{d}{dt}\begin{vmatrix} q \\ \dot{q} \end{vmatrix} = \begin{vmatrix} 0 & I \\ |\alpha|^{-1}|\gamma| & |\alpha|^{-1}|\beta| \end{vmatrix}\begin{vmatrix} q \\ \dot{q} \end{vmatrix} - |\alpha|^{-1}|\delta||\omega| - |\alpha^{-1}||F^*|$$

This aspect can be used in the design of orthosis elements, in the synthesis of control based on dynamics, and in determination of the man-orthosis interactions.

Focusing again on the control strategy, we are convinced that the automatic adaptation of discrete state parameters (e.g., when changing the gait speed or the slope of the surface) has to be on the dynamic level with the local control.

II INDICATION AREA FOR THE HO

Generally speaking, indications for HO treatment are the lesions and disorders of the central and the peripheral nervous system, as well as myopathies that have inflicted severe compromitation of locomotion functions.

1. The clinical symptomatology of diffuse lesions or disorders of the central nervous system and of brain damages is spastic quadriparesis (more or less manifested), with possible laterality or enlarged disability of lower

limbs (with respect to upper extremities). These symptoms can be observed in different varieties and with a different degree of locomotion insufficiency. We consider the functional classification of demyelinization disorders into stadia, by Mc Alpine and Compston (1952), useful for approximate indications of HO treatment, regardless of whether the disability is definitive or just a stage of a progressive disease. Patients whose functional status corresponds to one of the stadia IV or V are selected for bracing.

Stadium IV. The ability to move about the house. (Able to move about the house with difficulty, leaning on furniture or on crutches. Unable to climb the stairs).

Stadium V. Unable to move in the house. (Confined to the shair or the wheelchair.)

The indication has to be narrowed down to those patients that fulfill the following requirements:

- Preserved learning ability.
- Absence of intensive involuntary movements.
- Absence of significant balance disorders.
- Absence of lower limbs contractures.
- Functioning upper extremities and shoulder muscles.

Simultaneous existence of lesion of the peripheral nervous system is a shortcoming since it limits or prevents the use of FES in the scope of the HO.

Preserved deep sensitivity is considered highly favourable for a positive outcome of HO treatment (in some patients, this could result in walking aided by the HO, without the help of hands).

The model proposed for this category of patients: SFMO as the external skeleton, FES as the biological actuator. CA are not used at all or as a mere supplement to FES.

2. In patients with disorders or injuries of the spinal cord, the functional deficiency is manifested by total or partial spastic paralysis of musculature below the level of injury. (Cervical localization causes, aside from central type incapacities, the peripheral motor neurons´ incapacity of upper extremities).

In determining the indication area for HO treatment, we consider it best to use Coghlan´s classification by muscle function, because it is aimed at evaluating the potential for the supstitution of locomotion insufficiency by bracing.

Group I. Without functions of the abdominal musculature.

Group II. Only the musculature of the upper abdomen is functioning.

Group III. Upper abdominal musculature + Leg musculature graded 2 or more.

Group IV. Complete abdominal musculature + Trunk extensors at least up to Th-12.

Group V. Complete abdominal musculature + Lumbal extensors + Lateral flexors graded 3 or more.

Group VI. Complete abdominal musculature + Lumbal extensors + Lateral flexors + Hip or knee activators graded 2 or more.

Patients of groups III - VI have indications for the HO, allowing that following conditions are fulfilled:

- Absence of contractures of lower extremities.
- Absence of strongly manifesting spasms.

If at the same time their is a lesion of the peripheral motor neuron of lower extremitites, the indications for treatment and selection of a HO model have to be changed due to restricted possibilities of FES use.

3. Concerning paraplegia and paraparesis, caused by lesions or disorders of the peripheral nervous system, (polyradiculoneuritis, poliomyelitis, lesions at the level of the cauda equina etc.), the possibilities of HO treatment are limited considerably since FES is droped out of the possible HO model. Patients from groups III, V and VI, according to Coghlan, would be eligible for HO treatment if the following conditions are fulfilled.

- The function of shoulder muscles and upper extremities completely preserved.
- Absence of contractures.

The hybrid orthosis for these patients consists of a SFMO that serves as the external skeleton, and of CA that function as joint actuators or supporting devices for the preserved muscular activity.

4. The application of HO on myopathias is limited to only a few indications. Since myopathia is characterized by the weakness of proximal muscle groups (pelvifemoral and shoulder musculature), there is a limited possibility of applying crutches. Also, the use of FES in the scope of the HO is symbolic or impossible. However, we can point out two groups of patients, with relative indications for the use of HO, allowing there are no contractures in lower limbs (and the patient is motivated for bracing - the unavoidable condition when bracing is concerned):

a) Pelvifemoral musculature graded 2+
   Shoulder muscles graded above 2.

b) Pelvifemoral musculature graded below 2+
   Shoulder musculature graded above 3.

The HO model is composed of the SFMO and CA that has a significant role in the process of getting up from the sitting position, and in stairs climbing.

The listed indications for different pathological conditions are results of mere theoretic studies, based on established facts of physiology and orthotics and on practical experience in individual treating with SFMO and FES. Appropriate absolutte and relative indication must result from practical testing and clinical evaluation of the application of the HO on all proposed groups of hendicapped.

III REALIZATION OF THE HYBRID ORTHOSIS PROTOTYPE

Potential patients for the HO, in its elementary form, were selected on the basis of the above approach. The elementary form of the HO is a combination of the SFMO (Popović, 1981), controllers for the above-knee prosthesis (Popović, 1983; Tepavac, 1984), and FES (Kralj, 1980).

The self-fitting modular orthosis has been modified for the purpose of experiments with the handicapped in order to obtain an elastic (controlled) extension and electrical control of joint locking. The locking device is based on friction and is activated by a micromotor. The bionic sensor is a set of switches built-in the shoe insole, and sensors for joint angles and for the angle with respect to the vertical axis.

A double-channel stimulator with rectangular impulses is 3 μs wide and with hight $V \leq 100$ V, having 30 Hz frequency.

The construction of the microcontroller was performed with a 8085 processor. Patients from the group of spastic paraplegics with lessions on the thoracal level (Th 4-6) were selected as the best suited for the treatment with the given model of the HO.

The strategy of sequential, ipsilateral-contralateral performance was selected. The sequence for each side can be separated into a series of discrete performance. The control vector should have four binary components.

- Knee locking (0 or 1).
- Standing up, unaided (0 or 1).
- Stimulation (flexion or extension) (0 or 1).
- External energy added (flexion or extension) (0 or 1).

The control vectors for the initial state (standing up) are:

$V_{right} = V_L$

$V_{right} = V_R$

$V_L(1,0,0,0)$

$V_R(1,0,0,0)$

Considering the right leg to be ipsilateral, the series of discrete states for walking on level ground is shown in Fig. 3.

The testing of the hybrid orthosis, based on experience acquired in using the SFMO and FES, was divided into several phases

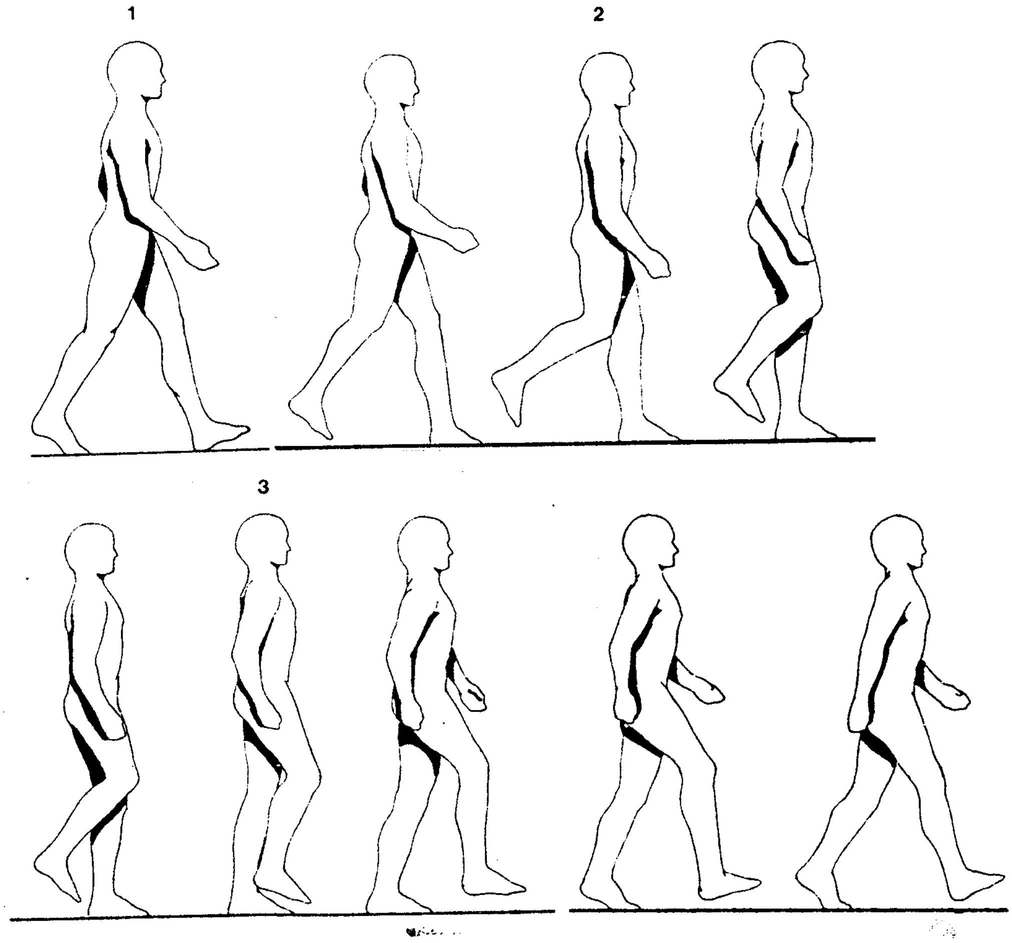
- Training the patient to use the SFMO.
- Preparation of the patient for FES.
- Application of FES in training the patient to stand up.
- Application of FES in training the patient to walk.
- Adjusting program parameters for automatic control of the HO.
- Training the patient to walk aided with the HO.

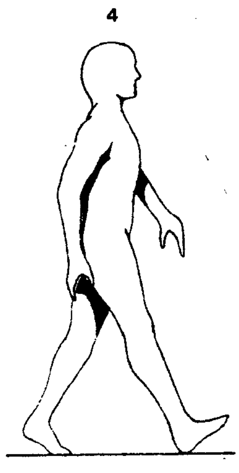
The plan for the rehabilitation of the patient with the help of the HO begins in the state of rest, by the use of FES for improving the trophesy of the m. quadriceps bilaterally, and for developing extensional sinergisms. Individual adapting of the SFMO and soft interfaces, and standing up exercises with the help both of the SFMO and the FES (separatly and combined), are conducted in the phase of getting into the upright position. The training of flexion sinergisms also occurs in this phase as well as preparations for walking. The next step is to master getting up and sitting down with the help of the HO. The training for walking is performed gradually; first a step forward with one leg is made with the help of parallel bars. Later on, gait sequences are combined and parameters of the software program are adjusted, still using parallel bars. Finally, walking without the use of parallel bars is attempted, using the walker and later on crutches. Training for gait sequences with the use of parallel bars and transition from parallel bars to the walker is the most complex part, regarded from the standpoint of the patient as well as from the aspect of parameters´ adjustment and HO system correction.

CONCLUSION

This paper comprises the mechanicistic and the neurophysiological approach to bracing paralysed lower extremities. The neurophysiological approach has been simplified and reduced to the use of FES, CA and AI. The indication area has been selected using practical experience in bracing and theoretical abilities of the HO. The HO is composed of a SFMO, CA and FES. Parallel operation of the dual system is controlled by a set of bionic sensors, using AI and artificial reflex arcs.

Preliminary studies with patients show that the HO can be realized, and that its possibilities are far greater than those of the constituting components. The advantage of this approach is the openness of the system i.e., the possibility of numerous combinations of individual elements in future development of the system and further improvement with new hardware and software elements.





	1	2	3	4	5
LB	+	-	0 (+)	+ (o)	0
LF	0	+	0	0	0
LE	0	0	+	0	0
RE	0	0	0	0	0
RF	0	0	0	0	-
RB	0(+)	0(+)	0(+)	0(+)	-

Fig. 1

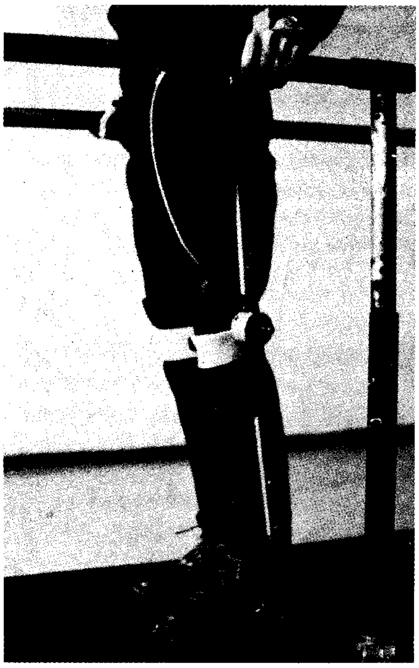


Fig. 2

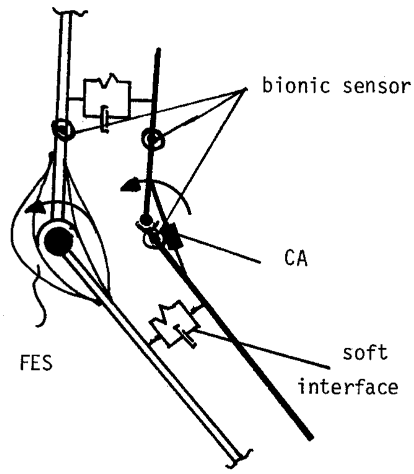


Fig. 3

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