MODEL BASED FES CONTROL UTILIZING FORMAL AND NATURAL LIKE SYNTHESIS OF MUSCLE ACTIVATION

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ABSTRACT

The control modes in prosthetic, orthotic or FES means for locomotion restoration were considerably enhanced in the last 30 years. Nevertheless, the control problems are still not solved. Considering FES requirements, it is here proposed a mathematical model based FES control utilizing formal and natural like synthesis of muscles activation patterns providing the time and amplitude course of electrical stimuli. The principles adopted and developed by the nature in the evolution process providing tissue stressing reduction are the base for the formalised synthesis of muscles activation. It is shown and by in-vivo measurements confirmed that the muscular action is mirroring the loading stressing and consequently producing optimized tissue stressing reduction. The latter is resulting in long bones invariant stressing profiles. The proposed method and principles are discussed in this presentation, but no detailed computational schemes are presented. Proofs and criteria for the proposed model based FES control utilizing natural like synthesis of muscles activation are presented. It is believed that the here proposed model based FES control principles with the derived criteria are important elements for the development of future generations of FES systems.

KEY WORDS: model, FES control, locomotion synthesis

INTRODUCTION

First proposals for multichannel FES systems for movement restoration were presented nearly 30 years ago [1]. Already at that time far reaching control principles were proposed. As a proof we are depicturing Fig. 1 after Vodovnik et al. In essence until today the research has been focused into the problems of how to fill in the proposed "blocks" with adequate criteria, technological solutions etc. It is also interesting that numerous researchers have more or less reinvented most of the principles already proposed in 1965 [1] as it will be recognized from our further discussion. According to developments followed the practical clinical experimental multichannel

FES systems were first introduced to stroke patients [2], and also for hands grasping enhancement in patients with cervical lesions [3]. Later in the seventies FES systems were developed for locomotion enhancement in spinal cord injured patients [4,5,16]. Characteristic for eighties in FES development was a rapidly growing interest and the development of improved technology for better application and clinical utilization. In the same time it became evident that the control of multichannel FES systems and in general of complex movements functions is a hard and unsolved problem. It seems that because of primitive control solutions the obtained quality of FES enabled movements, functions, endurance and practicality is very limited. Therefore in spite of the present state of technology and constant patients demands practical and daily utilization of complex FES system is unlikely to happen until the control dilemmas and problems are solved adequately. The control problems of complex movement functions restoration represent the key topics for many research groups for the last ten years. Consequently many different control principles have been proposed. In our presentation we are going to limit the discussion to the problems of gait restoration. The here presented principles do apply also for stroke and CP children movement restoration by means of FES.The control scheme of Vodovnik [1], Fig. 1, includes sensory feedback, closed loop joint angle servocontrol and the use of a special purpose

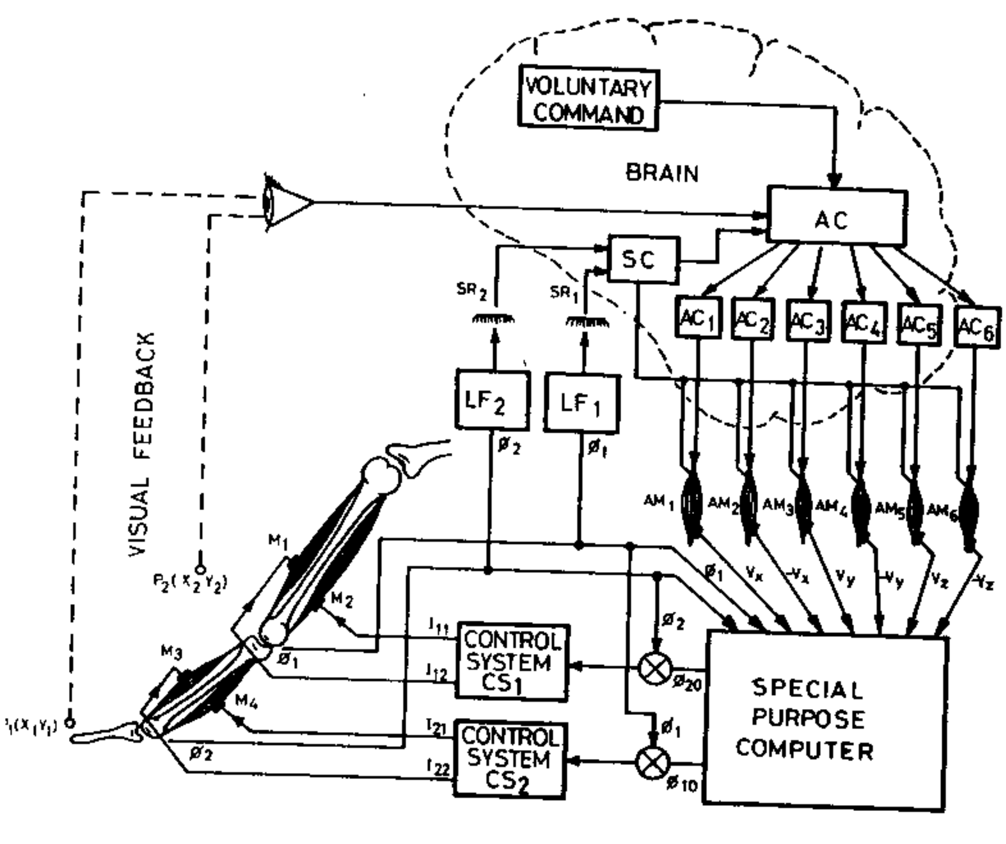


Fig. 1

computer. The control information is obtained via action of normally innervated muscles. Different principles control strategies and approaches were proposed in the last 25 years and we are going to comment some of them. Already in 1966 Tomovic et al. [7] proposed a finite state approach to the synthesis of gait control. The same author in 1984 [8] proposed control of assistive systems to be performed by means of external artificial reflex arcs and in 1987 adaptive reflex control was proposed at this conference [27]. It should be noted that FES systems incorporated FES activated reflexes as elements of external control already in the systems proposed in 1980 [15]. In general the practical applied systems for movement restoration utilized simple control schemes particularly in FES because of practicality reasons. Most of the FES systems developed from 1983 on adopted the principle of memorized and triggered FES sequences. These sequences are based on average EMG patterns like Maršolais et al. 1983 [9]. Similar system utilizing epineural implanted electrodes, was proposed by Thoma et al. [10]. At Wright State University, Petrofsky et al., 1983 [11] proposed computer controlled walking incorporating feedback principles in a similar manner as proposed by Vodovnik [1]. In 1986 at this conference Popović et al. [12] proposed the control for a hybrid powered orthosis.

Direct computer controlled electrical stimulation was proposed by Chizek et al., 1988 [13] emphasizing muscular properties and a discrete event model with control goals for restoring of locomotion functions. Andrews et al. , 1989 [14] proposed the rule-based control of a hybrid FES orthosis for assisting paraplegic locomotion. This system executes the information of the system in a hierarchical manner adapting the finite state approach of control. An interactive principle for controlling a hybrid gait system was proposed by Phillips, 1989 [15]. Because of simplicity reasons McNeal et al., 1989 [25] studied open-loop control and Popović et al. in 1989 [26] proposed the sensory driven control for gait restoration.

This rather brief review of control principles proposed for movement restoration or synthesis rises the question why so many different control systems have been introduced. Interesting enough is also to discuss why so many approaches have not solved the problem. Comparing the current FES systems and obtained results regardless of the utilized technology or control principle it can be concluded that more or less the achievements including practicality, gait quality, endurance, efficiency etc. of the different systems utilized for movement restoration in complete SCI patients are very alike. The simplest control mode in which the patient himself is controlling the FES timing [6] provides comparable results to the rather complicated computerised systems. In the latter case as in many previously mentioned systems the composition of FES sequences is rather subjective. Common to all the described control principles is that they concentrate on muscle properties and attempt to control the muscle contractions in a manner to ensure the subjectively determined joint torques or/and the prescribed joint angle trajectories. In respect to the body masses and muscular skeletal system configuration for an adequate control additional quantitative system elements have to be included into the control scheme. Until the last several years this has not been the case and many unsolved questions remained [17]. Several investigators started to introduce formal system modelling to be used for solving the control issues on a system level like the standing stability, control strategies, feedback design [18] or synthesis of rhythmic movements like joint trajectories for gait [19]. The synthesis of FES sequences on an execution level after the required joint torques were determined was proposed in [6, 20]. We consider this approach to be an important step forward because the properties of the musculo-skeletal system functioning as used by the nature are utilized for FES sequences generation. This paper discusses this approach and the advances made in the last several years.

METHOD PRESENTATION

Already in 1986 [20] it was proposed to develop means for mathematical synthesis of FES sequences. The main disadvantage of most of so far proposed methods for obtaining activation patterns for muscles is confined to the fact that only properties of the muscles were considered. Muscular function cannot be separated from the bone and joint function [21, 6, 20] and therefore from the nature and by evolution adopted principles and criteria with constraints for muscles action which must be obeyed. If this is not the case unefficient use of muscular power results and secondary pathologies can develop. It was proven in vivo that muscular action does not only provide the joint torques enabling movement, but serves also for stress reduction of bone tissue. In such an arrangement the overall material used for building the system is minimized and the energy efficient use maximised [21]. It is evident that new generations of FES systems need to be introduced following the idea expressed in Fig. 2.

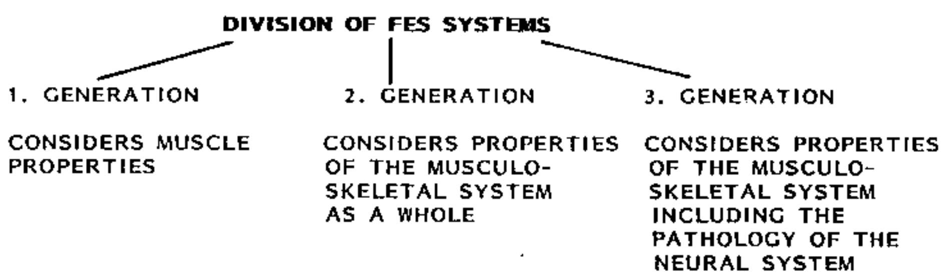


Fig. 2

The proposed method of formal synthesis of FES sequences is considering the properties and functioning principles of the whole musculo-skeletal system and is establishing the base for developing of the second generation of FES systems. Therefore, the skeletal system and its interaction principles with muscular function must be included into the FES synthesis process. Muscles, as formulated by Pauwels [21], act as tension bands for reducing bending stressing of bones. Bone tissue alike other natural materials can withstand several magnitudes higher compression stressing if compared to bending stressing. In Fig. 3a one may observe that muscular action mirrors and compensates the bending stressing at a cost of increased compression stressing. For instance if the loading and stressing caused in Fig. 3a is resisted by muscle action as depictured in Fig. 3d the bending stressing is reduced at a cost of doubled compression stressing. Similar circumstances apply for situations depictured in Fig. 3b and e and Fig. 3c and f. This, by theoretical studies obtained, rule of stressing reduction was in vivo tested and confirmed with experiments [22, 24]. The explained principle of muscular action is valid also during dynamical system stressing of the femur and tibia-fibula bones and remains unchanged regardless of the posture. The shape or profile of bending stressing is invariant to loading, posture and also function. Therefore, it can serve as a reference in our calculations while performing mathematical synthesis of FES sequences. In this regard also symbolic computational approaches are interesting and may speed up the process. In Fig. 3b the bending stressing has a shape of a triangle. Fig. 3c depictures some of our results obtained at two different postures for the tibia-fibula bones and for the femur bone.

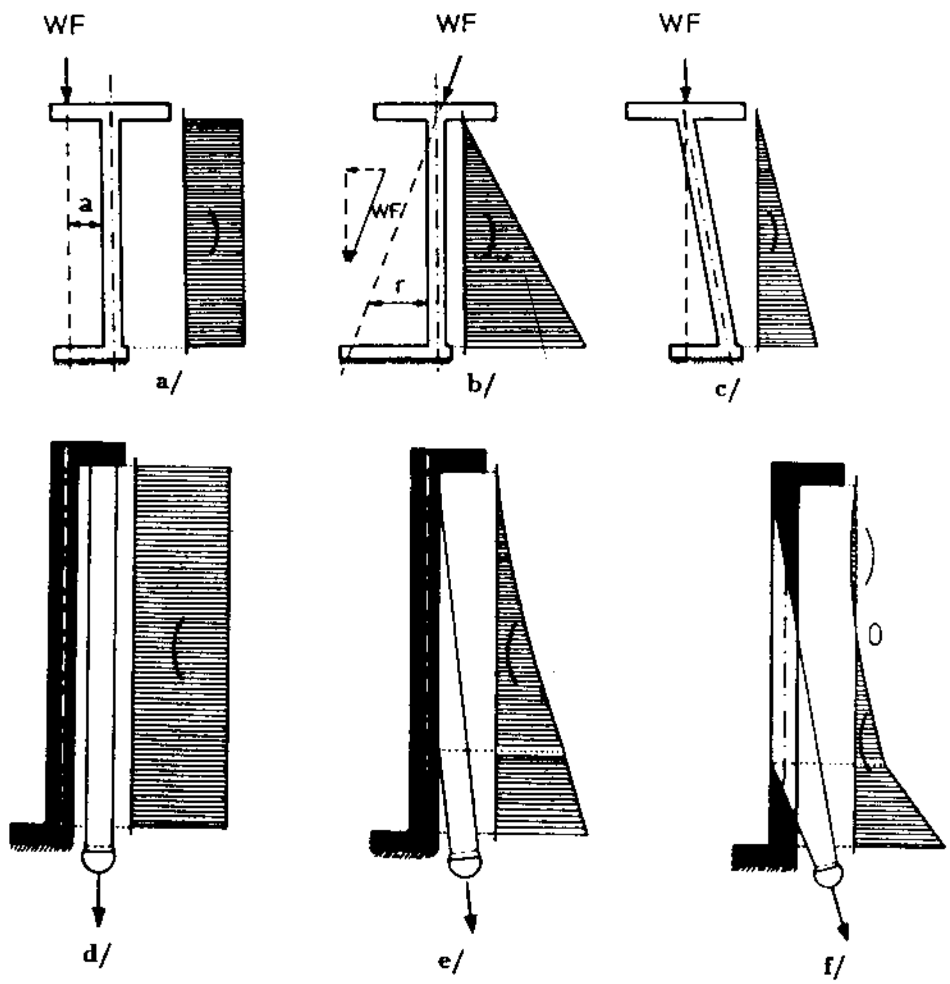


Fig. 3

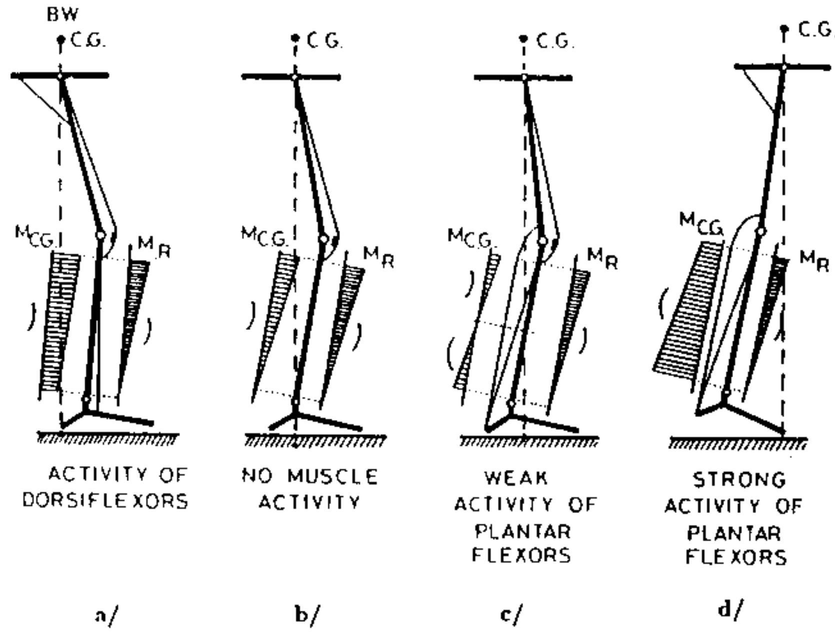


Fig. 4

It was interesting to find out that our results did in principle confirm in vivo the theoretical models of Pauwels [21] as depictured in Fig. 4 for the sagittal plane. The bending stressing in the sagittal plane for the femur is a triangle, having its top at the femur neck and its base at the knee joint level while for the tibia and fibula bones the triangle base is close to the knee joint and the top at the ankle joint. For the frontal plane the same principles apply. Observing Fig. 3c, d and Fig. 4 it is evident that the large gravitational stressing is due to muscles action substantially reduced and always converted into an invariant shape. This is valid for all our experimental results. Muscular action is reducing tissue stressing and this principle also applies for joint pressure reduction and preventing the joint structures from over stressing and consequently from the development of secondary pathologies [23]. Properly selected and activated muscles ensure minimal and adequate joint loading, by displacing the passage of the resultant force to the inner joint areas. This principle is illustrated in Fig. 5. For the resultant passing close to the joint area border the stressed area is reduced and according to the stress mechanics principles the pressure must substantially increase. Therefore, the muscle activation must obey the criteria for reducing joint stressing and ensure that the resultant never passes too far out of the center joint area.

So far we have proven in a simplified manner that there are four main criteria to be observed for muscle activation:a) muscles and their activities are selected to deliver the requested joint torques obeying muscular mechanics and constraints;b) while satisfying the a) condition the constraints stated in criteria for active muscular reduction of bending stressing must be obeyed, and) after a) and b) are satisfied the boundary condition or criteria for proper joint loading and over-stressing must be obeyed;d) after

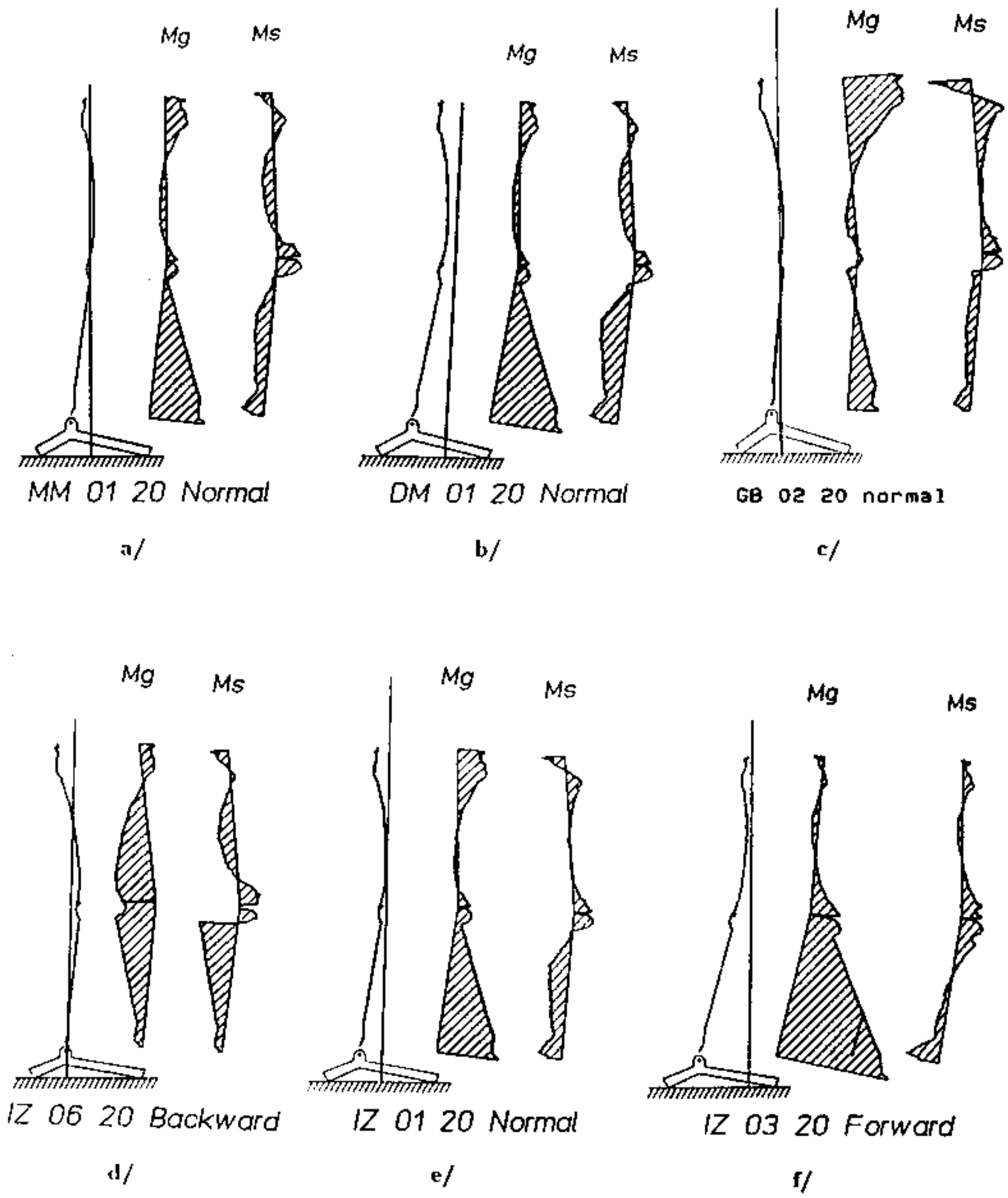
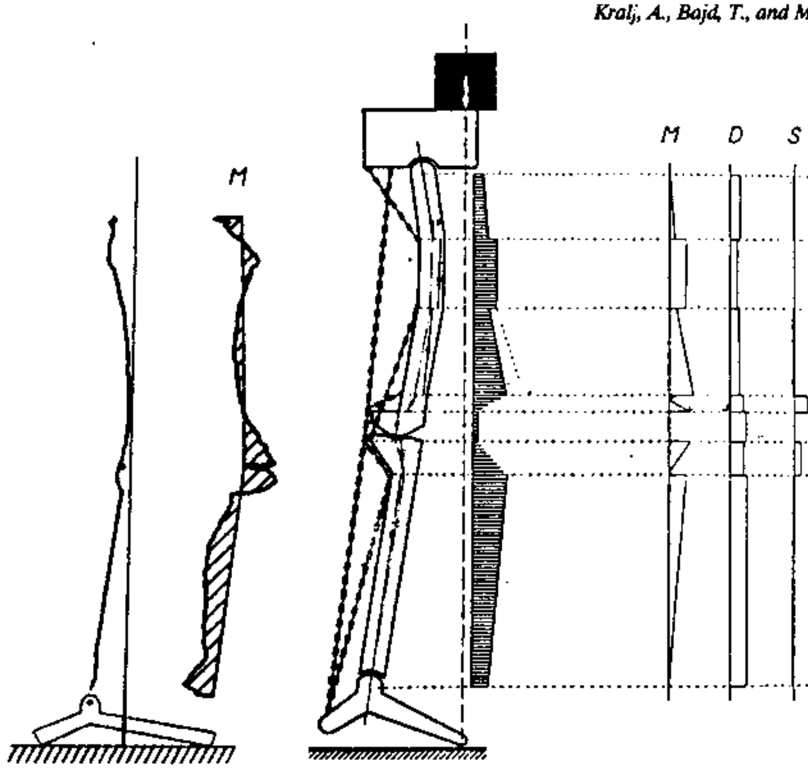


Fig. 5

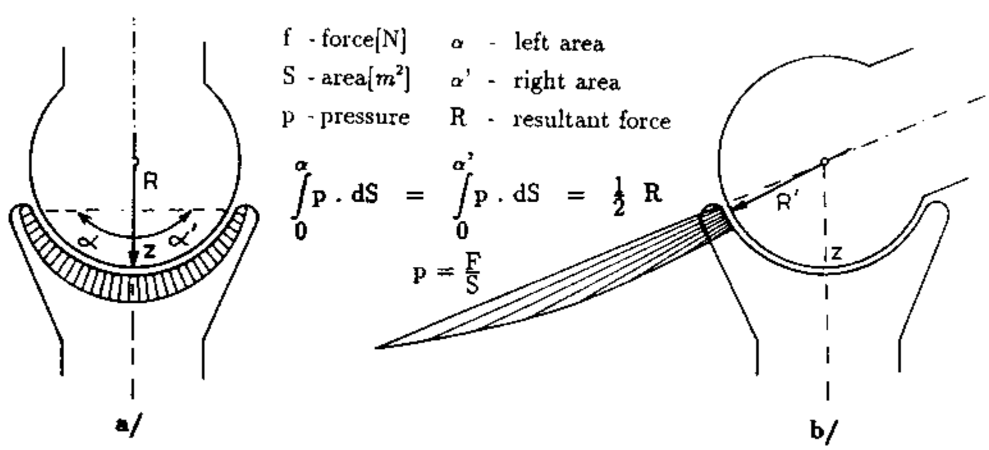
requirements a), b), and c) are satisfied also the supplemental criteria for ensuring optimality and efficiency are to be included.

It is not the aim of this paper to deliver detailed algorithms for the mathematical and model based synthesis of FES sequences. Rather the general criteria for muscular



a/ b/

Fig. 6



a/ b/

Fig. 7

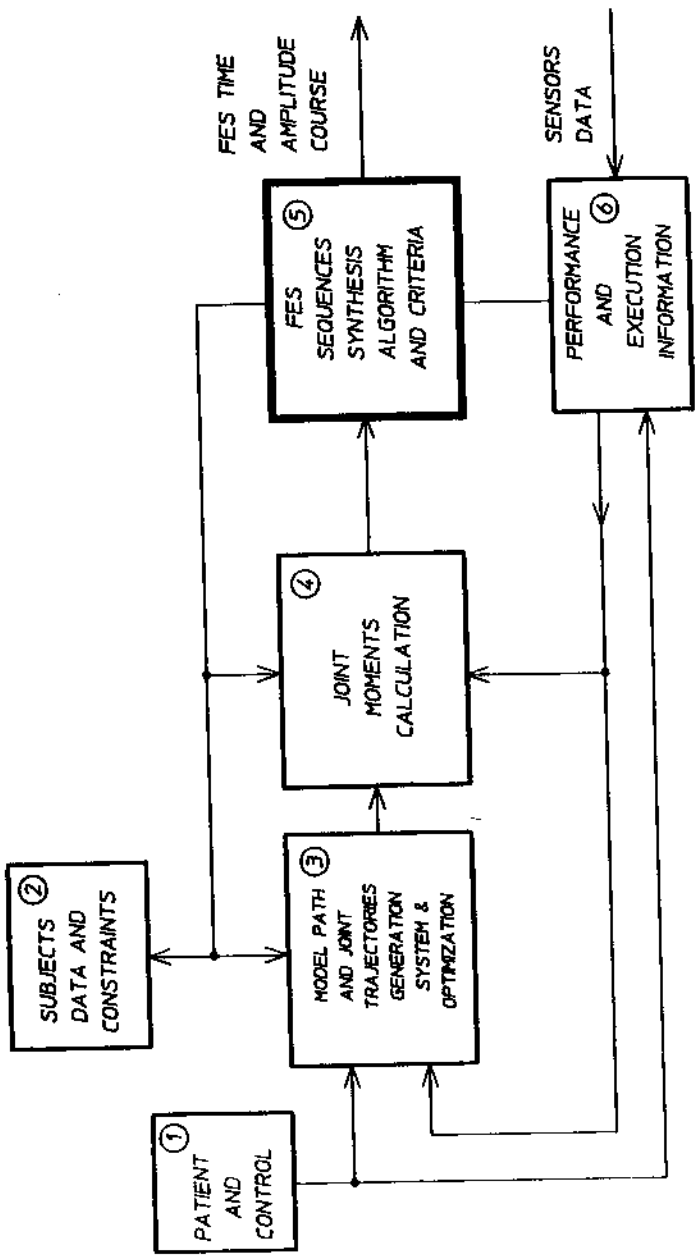

FES TIME AND AMPLITUDE COURSE
SENSORS DATA
5 FES SEQUENCES SYNTHESIS ALGORITHM AND CRITERIA
6 PERFORMANCE AND EXECUTION INFORMATION
4 JOINT MOMENTS CALCULATION
2 SUBJECTS DATA AND CONSTRAINTS
3 MODEL PATH AND JOINT TRAJECTORIES GENERATION SYSTEM & OPTIMIZATION
1 PATIENT AND CONTROL

Fig. 8

activation are presented. These criteria and procedure for FES sequence synthesis utilizing the explained muscular activation criteria are ensuring natural like synthesis of muscular activation in time and amplitude course. The here proposed methodology and procedures apply to the execution level while any applicable methodology for the control and calculation of joint moments (trajectories) on the system level may be incorporated. The block diagram presentation in Fig. 6 is illustrating principally the here proposed model based FES control utilizing formal and natural like synthesis of muscles activation.

The formal and here proposed FES sequences synthesis is performed in block 5. Considering the modelling procedures described in [24] and here [22] many possible approaches for the development of algorithm for the synthesis of FES sequences using the here proposed methodology can be carried out. Regardless of the many possible calculation or algorithms development possibilities the principles stated here remain valid and the results are ensuring natural like and formal objectively calculated activation of muscles.

DISCUSSION

The current FES systems for locomotion restoration show inadequate functionality, endurance and practical difficulties in daily use. Functionality with endurance can be enhanced with technological improvements only to a certain limit. It is believed that important functionality and endurance improvements can be achieved with improved control. Present FES systems consider only activation and biomechanical muscular properties and therefore are in prolonged chronic use, prone to secondary pathologies development, not mentioning the difficulties of inadequate energy consumption and hence low endurance. Muscles function cannot be studied or controlled without considering osteo and joints mechanics. This was proved with the results obtained [21, 24, 22, 6]. The muscular activation criteria proposed here consist from four important elements: the joint torque criteria, the criteria for bending and joint loading stressing reduction and the optimization criteria. Current systems consider only the joint torque criteria and partly the optimisation criteria and are in regard to natural biomechanical control and optimisation inadequate and limited. The concept of invariant bending stressing shape of bones enables mathematical model based natural like synthesis of muscle activation providing timing and amplitude course corresponding to the required joint torque obtained by the FES control at the systems level. On the ground of the explained fundamental knowledge it is possible to derive computational and optimisational algorithms not only in classical formal form but also due to invariant bending shape, to introduce in this process symbolic calculation procedures. The here proposed and developed methodology for muscle activation synthesis can be combined with many arising control procedures aimed for the control problem solution on the system level. There is no doubt that the methodology developed delivers natural like activation and loading patterns to the tissue and gives possibilities for adequate endurance increase as it gives efficient protection against secondary pathology developments. The proposed criteria and methodology represent a solid base for second generation FES systems control software and hardware development.

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