MATHEMATICAL SYNTHESIS OF FES SEQUENCES

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The simple gait mode utilizing 4-channel FES and incorporating the flexion reflex withdrowal movement has proven to be feasible for level and stair walking of adequate selected SCI patients. At present regardless of the stimulation technique and employed control mode particular the performance and control of FES enabled functions need substantial improvement. This presentation is proposing a method for objective biomechanical based online mathematical synthesis of FES timing and also amplitude control. This method utilizes the principles of osteomechanics and basic construction principles of the musculo-skeletal system. These principles and knowledge are employed for synthetizing FES sequences. Proposed are two criteria in this regard: The primary and secondary muscle activation criteria. The presentation is explaining the method and how it will be tested. The methodology of testing is also presented in brief.

INTRODUCTION

FES enabled short term standing in SCI patients was reported already in 1963 by Kantrowitz /1/ and later by others /2,3,4/. Forward progression was reported in /2,4/. In 1978 clinical utilization of FES enabled biped gait in parallel bars was reported /5,6/ and later also crutch assisted walking /9,10/. Nearly at the same time achievements of FES enabled gait were reported at several research centers /11,12,13/ and stair climbing of SCI patients by means of FES was also shown /11/. At present regardless of the stimulation methodology used the fundamental principles of gait composition and control are very similar if compared among research groups. The main characteristic is the very subjective FES stimulation pattern composition and selection. There are two main approaches in this regard: A) the menu mode, where the stimulation sequences are stored in a memory and activated or triggered by the patient piece by piece /11,12,13/; B) the trigger mode, where the patient himself is triggering and controling the entire process and no event is stored at all /8,10/. In the menu mode the patient has less control and is acting more or less as a robot, but this mode has advantages in regard of easy adding of new functions and stimulation sites. Mode B enables more versatile control to the patient, requires more learning and experience and additional functions with stimulated muscles are added with difficulty. In the menu mode 8 or twice or even three times the number of stimulation sites were easy introduced /11,12,14/, while for the trigger mode mostly 4-channels of stimulation are so far utilized and seldom 6 stimulation sites. The latter mode is keeping the number of stimulation sites low also due to the incorporation of the flexion reflex for obtaining a similar movement to the swing phase cycle in gait. As described each mode, A and B, has some advantages but also disadvantages. In principle important are the obtained results and performance. Common to the present results regardless of the gait composition and control mode utilized is that the composition process is entirely subjective and based on try and error search for the suitable stimulation pattern. In A mode predominantly this is done by professionals for the patient, while in B mode the patient obtaines training and is composing the events himself in real time and in regard to his abilities, needs, obstacles and general walking path situation. Also the performance of locomotion functions obtained are regardless of the composition mode nearly the same. To every one it is clear, that for a well executed function like making a step, good orchestrated activity of a number of muscles is required. The FES activation pattern also called stimulation sequence must fulfill several requirements: timing and amplitude-strenght selection in time. In FES systems this is simplified that according to a trigger the varius muscles activations is specified as a variable function of some other variables, but is rather preset for a constant value. In A mode it is easier to incorporate variable amplitude versus time. It requires only more memory in the programmer of stimulation sequences, but is rather time consuming and difficult to change (reprogramming). In B mode the amplitude is for each channel preset by the patient and can be in principle at any time changed. The so far obtained FES enabled locomotion functions are far from being close to normals performance and need substantial improvements in many aspects: quality, controlability, robustness,.. but also in better composition of stimulation sequences. One may conclude, that the whole FES field and even locomotion rehabilitation field in general is lacking objective and fundamental sciences based function synthesis rules, taking in consideration also the patient constrains given because of pathology and/or preserved locomotor system state. Also the invariances of the human system construction should play an important role in the function synthesis regardless of the means utilized. Such thinking is governing our research work for a long time. This presentation is describing our efforts and results obtained in regard of defining scientific based fundamentals for FES stimulation sequence synthesis and muscle activation principles in general. Our research is focused into the fundamentals of locomotion system construction and into the understanding of elementary functions which are composing the human locomotion in general. We believe that by the evolution developed locomotor system in man does reflect important principles, constraints and invariants which are essential for the muscle activation synthesis and understanding of neuromuscular control. At this point we shall notice that all the approaches so far for FES sequence synthesis have in detail studied the muscle, but neglected totally the supportive structure, the skeletal system and joints. We believe that the musculo-skeletal system with joints composition, its biomechanics, constrains and principles of construction is defining the criteria of muscle functionning and reflects in principle also the neuromuscular control perse. Therefore the essence of our approach is to incorporate the skeletal system - bones and joints in the stimulation sequence synthesis and not only the properties and constrains of muscles. By doing so we hope to develop new and scientific based fundamentals for the mathematical and objective one line stimulation sequence syntheses. The later being the software of future generation FES locomotion rehabilitation systems.

WORKING PHILOSOPHY

According to the needs our research is aimed to develop:

1. A method for mathematical synthesis of locomotion sequences.
2. Biomechanical and control strategies for efficient and natural use of muscle power.
3. How to use pathologically imposed constrains in synthesis of locomotion.
4. Muscle substitution and coordination principles and limitations and
5. The knowledge, principles and fundamentals for FES control software.

Our main working philosophy is constructed around the structure of the human locomotor system and reads: Biomechanical sturcture of the locomotor system reflects important constrains, invariants and criteria for neuromuscular control. Understanding the constrains, invariants, and criteria is essential for FES control. Also important in pathology these boundary conditions are changed and pose additional limits. Therefore less possibilities and substantially narrower boundary conditions apply for muscle activation synthesis. In our approach the patient control and possible modes of trajectory and movement planning are developed according to criteria of bone loading. We would like to find mathematically and objective based the optimal muscle activation (timing and amplitude-force course) in real time. There were attempts to optimize muscles coordination for sharing the torque of a joint. These early attempts used linear/nonlinear criteria for sharing torque among muscles and incorporated also the main muscle properties and sometimes also the physical dimensions of the skeleton /15,16,17,18/. First in 1969 a linear model /15/ for optimal muscle coordination was proposed. The essentials for such an approach are given in Eq. 1 and 2.

$$M_i = \sum_{i=1}^{n} r_i(\varphi)\ F_i\left[V(t),\ l/l_0,\ dl/dt,\ S, \varphi,\ t,\ I_{st}.\right]\ldots\ldots \qquad 1)$$

$M_i =$ requested torque across a joint

$i = 1,2\ldots.u$ number of muscles for sharing the torque

$\varphi =$ joint angle and r_i ( ) moment arm of i-th muscle

$V(t)$ = muscle status in time, trained, fatigued etc.

l/l_0 = relative muscle length

dl/dt = velocity of muscle shortening

S = physiological cross section

I_{st} = FES amplitude

$$\sum_{i=1}^{u} F_i \longrightarrow \min\ ; \quad \text{and} \quad 0 \leq F_i \leq Fi_{mx}\ldots. \qquad 2)$$

The optimization criteria is given in Eq. 2. Dul et al./18/ proposed a criterion based on an assumption that the endurance time of muscular contractions is maximized, hence muscular fatigue is minimized. Mathematical this criteria requires a non-linear mini-max optimization process with linear constrains. In /18/ they used the minimum-fatigue criteria requesting "maximization of endurance time of muscles with the shortest endurance time" ($T_i$min), for obtaining longest performance, Eq. 3

maximize the min of (T_i)
with $T_i = T_i\ (F_i, F_i mx, S_i)$ .... 3)
$i = 1,2..n$ no of muscles, F_i - force
S_i = % of slow twitch fibers

T_i is the endurance time. The solution of the proposed maximization leads to non-linear rather complicated computation, but the results seem good to agree with circumstances in natural activation of muscles. There were also attempts byother authors for calculating muscular activity /16,17,25/. Seireg and Arvihar /16/ developed a model incorporting 29 main muscles of one leg and used it for evaluating the forces in different functions like rotations, trunk leaning and stooping, but did not contribute basic rules suitable for muscle activation synthesis. Patriarco et al. /25/ made an evaluation of optimization models for the prediction of muscle forces during human gait and found that accurate anatomical data utilization is more crucial than the criteria used. Also here gait models and kinematics were employed, but no fundamental criteria of functionning proposed. Similar Crowninshield and Brand /17/ utilized a physiologically based criteria of muscle force prediction in locomotion, but did not propose fundamental principles underlaying muscle functioning, but rather EMG of normals. Nearly all the referenced research was directed in muscle coordination but not in finding primary principles of action. The question how to select muscles activity according to the kinematics in general was not discussed. How does muscle activity relate to the osteomechanics was not considered and left out. We believe that bone loading principles, osteomechanics and joint mechanics on a higher functional level determine muscular action. We call this level the principal muscle activation criteria. Therefore all the approaches referenced /15,16,17,18/ one may characterise for secondary criteria of muscle activation. So far this knowledge did not find practical use in any of the FES systems. This is probably due to the fact that problems on a higher level seek solution. Namely, logically criteria to determine when and why a muscle must be activated in principle. This criteria and knowledge can be characterized as principle muscle activation criteria.

METHOD DEVELOPMENT

The principal muscle activation criteria is important for FES sequence determination because it is based on the osteomechanics principles and takes in account also muscle properties.

To determine and find the principal muscle activation criteria and its fundamentals we searched the osteo mechanics /19, 20,21,22/ and accepted several proven and maybe not yet proven facts about the musculoskeletal system. Some of the rules and accepted facts are listed here in an order to support our proposal, for using this knowledge in synthesis of muscle activation. Some of these facts are recapitulated from /22/ and some added. Also figures 1-4 are redrawn after /22/. Weight transfer if equipotential in gravitational field is energy most efficient. Therefore nature has adopted this principle. Any nonequipotential moving masses while performing locomotion should be minimized. For scarcely obtained energy and it efficient utilization the weight should be in principle small. Therefore the following applies to the construction of musculoskeletal system:

1. Musculoskeletal system is constructed with the greates economy of material and mass (weight).
2. If each bone is built with minimum material then it is constructed and adopted by nature and locomotion to prescribed and determined stressing.
3. According to 2. the stressing is decisive given and must reflect muscle action (static and dynamic).
4. Muscles support and move weight.
5. Bones are most sensitive to bending stressing and can sustain very large compressive stressing /26/.
6. Bending stressing is most dangerous and caused by weight.
7. Bending stressing can be reduced in principle by tension bands and hence by muscles.
8. The musculo-skeletal system is constructed to ensure minimal bone stressing.
9. Muscles and ligaments diminish bone bending stressing, increase compressive stressing and act as tension bands.
10. Static effect of muscles is combined with its kinetic action so it provides tension bands action, moves weights and fixes the joints (stifness).

Because of the said and bullets 1-10 we proposed the following principal muscle activation criteria:

Muscles act to ensure minimized and uniform (in shape and magnitude) loading of bones (time and force amplitude pattern).

In principle it says that if bones are constructed to adopt their diameter and material in the cross section to the local stress, then along the bone the stressing is determined.

Next we are going to explain some of the principles and illustrate the said. If the stressing profile and shape is prescribed for a bone, then muscles have to act in a manner to compensate any stressing - loading to the given one. Therefore we have to examine these principles of muscle bone function for understanding the muscles arrangements across bones, joints and their activation. Fig.1 is illustrating the basic principle how muscle action can compensate bending stressing. It can be clearly seen that for muscle action combined with load action the bending stressing is compensated and as a result we obtain enlarged compression stressing. Such an action is associated to two joint muscles.Fig.2a,b,c displays benging stressing profiles for different muscle-bone insertions. For differnet bone loading geometries similar but opposite stressing profiles are obtained. Principle of Fig. 1 still applies. Fig. 2 b and d explains the basic action of one joint muscle. The geometrie of the skeletal system was adopted to the locomotion and as known loading of masses is not parallel to the bones. The later is advantageous because of shorter moment arms. Muscles are always added in a manner to mirror the loading and to obtain possible maximal moment arms and best bending stressing reduction.

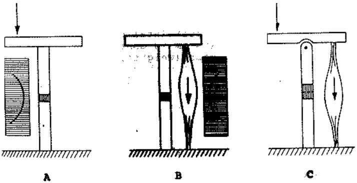

Fig. 1.

Observing of muscles insertion to bones in Fig. 3 is a good prove and illustation to the so far said. The tibial and femoral bone structure is shown indicating also how the bone crosscection area is changing. Principles of skeletal system structure and bending loading for different possible weight force WF are displayed in Fig. 4a, b,c,d and e.

The principle ob bending stressing shown in Fig. 1 can be applied also in cases of stressing displayed in Fig. 4 if utilizing the muscles action of Fig. 2. The explained principles illustrate that the principal muscles action criteria as it was stated has great potential to be valid and needs to be prooved in experimental work. Because of the principal muscle activation criteria

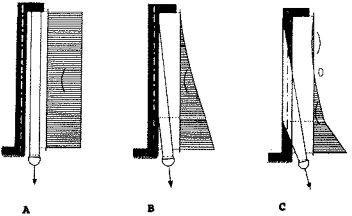

Fig. 2.

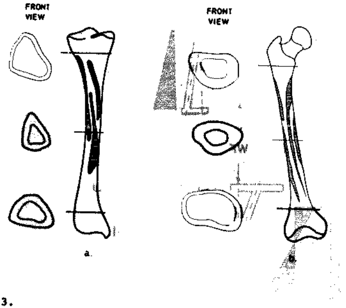

Fig. 3.

for ensuring minimal and uniform bone loading we are able to utilize it for obtaining and calculating the time and force pattern for each muscle. In case several muscles may be used the secondary criteria is employed to ensure best efficiency and mimimize fatiguing. In case experimental verification may proove the principal muscle activation criteria the FES and rehabilitation field may obtain a powerful tool for mathematical synthesis of stimulation sequences and a sound background is given for employing **feedback.** In addition means for biomechanical based strategies for efficient use of FES muscle power will be given. Also the imposed **constraints because of pathology can be considering the criteria incorporated easier and objective in the synthesis when reconstructing lost functions.**

EXPERIMENTAL VERIFICATION

All the said so far illustrates our research philosophy and is echoed in the experimental work aimed to test and prove the given assumptions and hypotheses described.

The validation of explained principles and muscle **activation** criteria is not a simple task. We decided to evaluate and prove our hypotheses in a more or less stationary experimental set-up. Normals and SCI patients are used for test subjects. The main problem is how to measure exerted forces by individual muscles Only non-invasive methods can be employed. Therefore in normals **we are going to measure surface and wire** EMG together with **the**

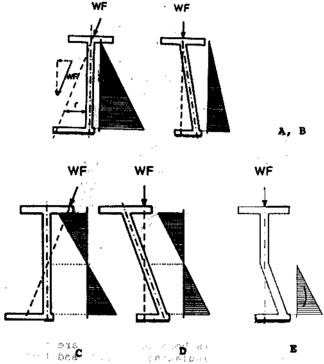

Fig. 4.

main biomechanical data. A force plate will be used and goniometers for obtaining kinematic and kinetic records of subject performance. The experimental set-up is shown in Fig. 5, **where the** EMG part is not depictured. For study and verification simple data collection is a sound requirement. Therefore if the subject is progressing in space it complicates the data collection. We **restricted ourselves to simple functions like standing, posture switching, standing-up and sitting. In patients the stimulation is provided via a 6-channel stimulator incorporating a MC 146805** E2 microprocessor /23/. This stimulator provides **2x2 key commands,** 2x3 linear potentiometric commands for amplitude **correction all** mounted and easy handled on the supportive device for the **patients' use.** The six channel stimulator is controlled by the IBM-**XT PC** which serves for **fast information** processing **requested for** closing the feedback loop. The I/O capabilities **to the XT** are 16-ch, 12 bit ADC (tc = 33 µs), 2x12 bit DAC (ts = 5 µs), 24 I/O PIA lines and a 5x16 bit timer. Any information processing of goniometric, force plate or EMG-data can be performed and doing so utilizing different principles for stimulation sequence generation.

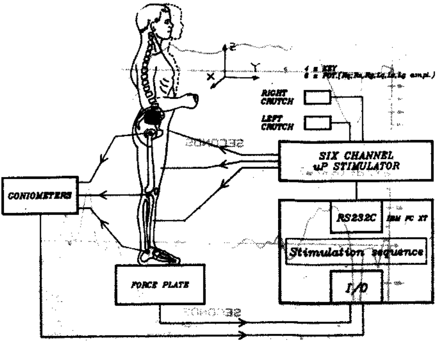

Fig. 5

The first data obtained using the system are promissing, and also the flexibility is adequate. Fig. 6 is displaying a record of anterior posterior ground reaction vector displacement Y /cm/, it derivative and EmG records.Already from Fig. 6 one may recognize the interplay of m.quadriceps action with m.gastrocnemius and soleus action. Surface EMG electrodes were used. The ankle joint axis was located at Y = 0. At present only standing-up and posture switching data are collected for comparison of performance among normals and to compose adequate functions in SCI patients by FES. The data collection for the evaluation and study for proving of the muscle activation criteria was already started.

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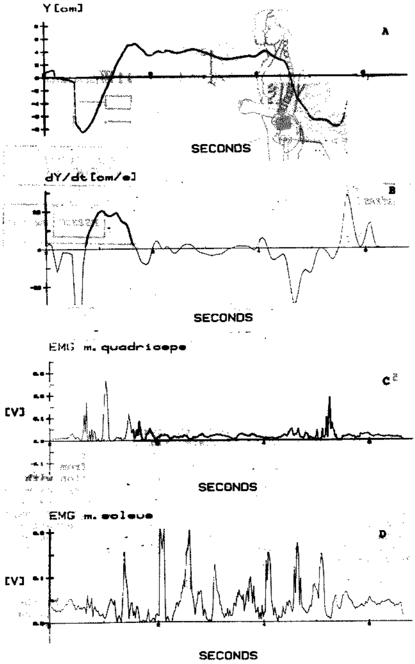
Y [cm]
A
SECONDS
dY/dt [cm/s]
B
SECONDS
EMG m. quadriceps
C
[V]
SECONDS
EMG m. soleus
D
[V]
SECONDS

Fig. 6.

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