FURTHER TECHNICAL IMPROVEMENTS OF MULTICHANNEL FES STIMULATORS USING MICROPROCESSOR CONTROL

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Abstract

The power and flexibility of microprocessor in control of complex systems motivated us to develop a microprocessor controlled six channel stimulator for therapy of paretic patients' gait. In the paper a comparison with later versions of six channel stimulators is given from the standpoint of prediction of stimulation for the next step based on the history of the gait, individual treatment of stance and swing phase duration for both legs separately and in addition the possibility of gait evaluation parameters. The limits of further sophistication of stimulation sequences are also discussed.

Introduction

Hemiplegia is one of the typical diseases of the modern world. Ussually it occurs as a consequences of cerebrovascular insult. In the developed countries this disease affects two to three people out of a thousand. It appears in all age groups; however , it is more common in middle age and in elderly people. Insult causes not only physical impairment but also psychological , social and vocational problems. Therefore, rehabilitation of such patients requires very complex treatment and FES is therefore only a part of rehabilitation.

Use of multichannel electrical stimulators is one of the most promising trends in the physical part of rehabilitation of patients with plegic or paretic extremity muscles. These lesions usually result in the loss, diminution or disorganisation of control over some muscles, although the muscles themselves remain capable of contracting under artificial electrical stimulation. Due to inactivity of individual muscle groups, permanent damage to the locomotor apparatus may occur. Multichannel surface stimulators (usually six channel - there are six major muslce groups in a leg for movements in the sagital plane) are intended for the therapy of hemiplegic patients' gait, and lately also for paraparetic patients. Compared with classical methods of physical therapy, a higher degree of improvement is achieved in a shorter period of time (3).

Their power and flexibility in control of complex systems motivated us to developed a microprocessor controlled six channel stimulator (Fig.1) for therapy of paretic patients' gait. Some part of it are functionally identical of very similar with previous, non-microprocessor controlled versions (2), others are improved.

<u>What is functionally identical?</u>

There is one pulse generator for all channels so the parameters of the stimulation pulses are the same (pulse frequency adjustable from 10 to 65 Hz, pulse width from 0.1 to 0.7 mS.) The amplitude can be set manually up to 150 V for each channel. The channels are coupled by optical isolators and output signals for all channels are delayed with respect to each other (time multiplexed), to avoid cross-stimulation between different electrodes. The stimulator is powered by six miniature power cells, which provide a minimum of 10 h of stimulation.

Graphical representation of the stimulation sequence set is of utmost importance for easy adjustment and alteration of the stimulation program by medical personnel. Stride time is represented by 16 discrete time intervals. In each of them, the stimulation of predetermined amplitude (which can be set for each of the six channels by rotary potentiometer) is turned on by a separate switch. In this way a nearly linear representation of stimulation in time is achieved. Another advantage of switch control is that several stimulation trains in a stride period can be formed. Some muscle groups (Fig.3) have two distinct activities during stride time (usually in the transition from heel-on to heel - off phase and vice-versa) and therefore two stimulation trains are needed.

The stimulation program is triggered for heel-on and heel-off phases separately via a heel switch mounted in the shoe insole. All stimulators (previous versions with discrete circuitry, microprocessor version with software) separate regular triggers (occuring during more or less cyclic gait) from erroneous ones (ocurring during shifting legs during standing, at double or uncertain heel contacts, those due to "grass" induced by the heel switch itself, or at an abrupt change of gait). The very unpleasant stimulation triggered at incorrect times is frequently prevented. All triggers which are not within the expected time interval for a given gait cadence (all heel-on triggers which occur after the heel-off trigger before the elapse of 25% of the temporal stride time and after 75% of the stride time, for example), and also triggers which are not in the right sequence (heel-on, heel-off, heel-on, etc.) are ignored.

The new microprocessor controlled stimulator has the same method of fixation on the patient and uses identical electrodes and heel-switches as previous versions (2). Its weight and dimensions are also practically the same as the last "classical" version, the MCS-5 (Fig.2).

What is improved?

In previous versions, the preceding stride times are measured, exponentially weighted and averaged and the duration of the stimulation sequences for the next step proportionally adjusted (2). Electronically, this is achieved by CMOS phase lock-loop regulation, where the input frequency is the patient's gait cadence and the output frequency (proportional to the gait cadence) feeds digital circuitry for stimulation sequence determination (used as clock frequency). This principle enables a free choise of gait cadence by the patient, but works well only when the ratio between heel-on and heel-off phase time is near 1. In the contrary case the shorter phase can be controlled with less than 8 switches, and in some cases even a gap between the longer and shorter phase without any stimulation may appear.

The microprocessor controlled version has an algorithm which predicts heel-on and heel-off phase time for the next step separately. Prediction is based on the history of the gait (last 3 heel-on and heel-off phases); the variation between the last two phases of the same kind (both heel-on or heel-off) is compared with same kind of variation one step earlier. Three different rules are used to predict the next gait phase according to formulae 1,2,3 and Fig.4.

prehistory values	predicted values	
$\lvert ST(n)-ST(n-1)\rvert < \lvert ST(n-1)-ST(n-2)\rvert$	weighed extrapolation	(1)
$ST(n) = ST(n-1)$	$ST(n+1) = ST(n)$	(2)
$\lvert ST(n)-ST(n-1)\rvert \geq \lvert ST(n-1)-ST(n-2)\rvert$	linear extrapolation	(3)

where

weighted extrapolation (1):

$$ST(n+1) = \frac{ST(n)}{2} + \frac{ST(n-1)}{4} + \frac{ST(n-2)}{8} + \frac{ST(n-3)}{8}$$

linear extrapolation (3):

$$ST(n+1) = \frac{ST(n)}{4} + \frac{ST(n-1)}{4} + \frac{ST(n-2)}{4} + \frac{ST(n-3)}{4}$$

$ST(n+1)$ . . . predicted time of next heel-on phase
$ST(n)$ . . . last heel-on phase time
$ST(n-1)$ . . . last but one heel-on phase time

Prediction for next heel-off phase is analogous. The algorithm was developed after studying computer recordings of some hemiplegics' gait patterns. It enables a free choise of gait cadence by the patient and adapts automatically to individual ratios of heel-on/heel-off phases. Therefore the stimulator allows the patient to shift toward his optimal gait cadence (5).

All our previous multichannel stimulators also have a fixed mode of stimulation ; the gait cadence(=cadence of stimulation)is manually set by medical personnel. It is used at the beginning of rehabilitation, to enable initiation of gait. Previous multichannel FES have heel-on/heel-off ratio in the cyclic mode of 50% / 50%; the new microprocessor FES has this ratio as 43,75% / 56,25% - this is much closer to normal gait. In this mode (without heel switches) the device can also be used as a muscle training apparatus.

The MCS 5 stimulator can be electronically divided into two three-channel devices.Each part can be triggered by one leg. It is intended for use in gait therapy of paraparetic patients. The microprocessor FES is improved, since it allows each channel to be triggered separately by the left or right heel switch. In this way the flexibility is further improved.

The microprocessor FES is also a gait evaluation device, which can calculate basic statistical parameters of gait:

- average heel-on phase (for both legs)
- average stride time
- standard deviation of heel-on phases (for both legs)
- symetry (average left heel-on ph./average right heel-on ph.)
- number of steps analyzed (up to 2047)

These parameters are presented in sequence on a four digit liquid crystal display. They enable us to estimate the degree of improvement in the rehabilitation process.

The microprocessor FES memorize four different preprogrammed stimulation sequences - this enables faster and more exact determination of the optimal stimulation sequence by comparing the gait under slightly different preprogrammed sequences, which can be changed very easily. The stimulation sequence must be adapted to each patient individually. In practice, channels are applied successively on the basis of visual observation of gait pattern.

Another big advantage of the microprocessor controlled stimulator is its flexibility. Since it is still a research tool different applications and modifications are possible merely by changing the software.

Limits of multichannel stimulation

Are 16 intervals for one stride time enough for exact control? Because muscle response to FES is stochastic in nature, and since stride times and(also the ratio between heel-on and heel-off phase) vary from stride to stride with hemiparetic patients by 3 - 10% (sometimes over 20%), too fine control is useless. Since the actual pattern of muscle deficits is covered by rectangular trains of stimulation pulses (which is a very rough approximation), the effects of a stimulation slightly too short or too long can always be compensated for by a slightly higher or lower amplitude. The next and most rigorous reason for "finitely accurate" controle of stimulation is our limited knowledge in teh synthesis of stimulation.

Stimulation is performed by surface electrodes and superficial muscle groups are primarily stimulated. The variability of muscle responses due to repositioning of electrodes and excessive pain sensitivity at high excitation amplitude are the major deficiencies of surface FES. All these arguments are so strong that we decided not to use graduated sequences in surface FES (6).

Some of those deficiences can be overcome by using implanted stimulation, where the deep muscles can also be excited. Implanted FES is of course only suitable for patients from whom natural improvement can no longer be expected. Multichannel implanted stimulation entails many problems, which cannot yet be solved. These include miniaturisation, the source of energy, better control and, probably the greatest problem, our present inadequate knowledge of natural control.

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ACKNOWLEDGEMENT

The investigation has been supported in part by the Slovene Research Council, Ljubljana, Yugoslavia, and the Research Grant 23-P-59231/F from the National Institute of Handicaped Research, Department of Education, Washington, D.C.

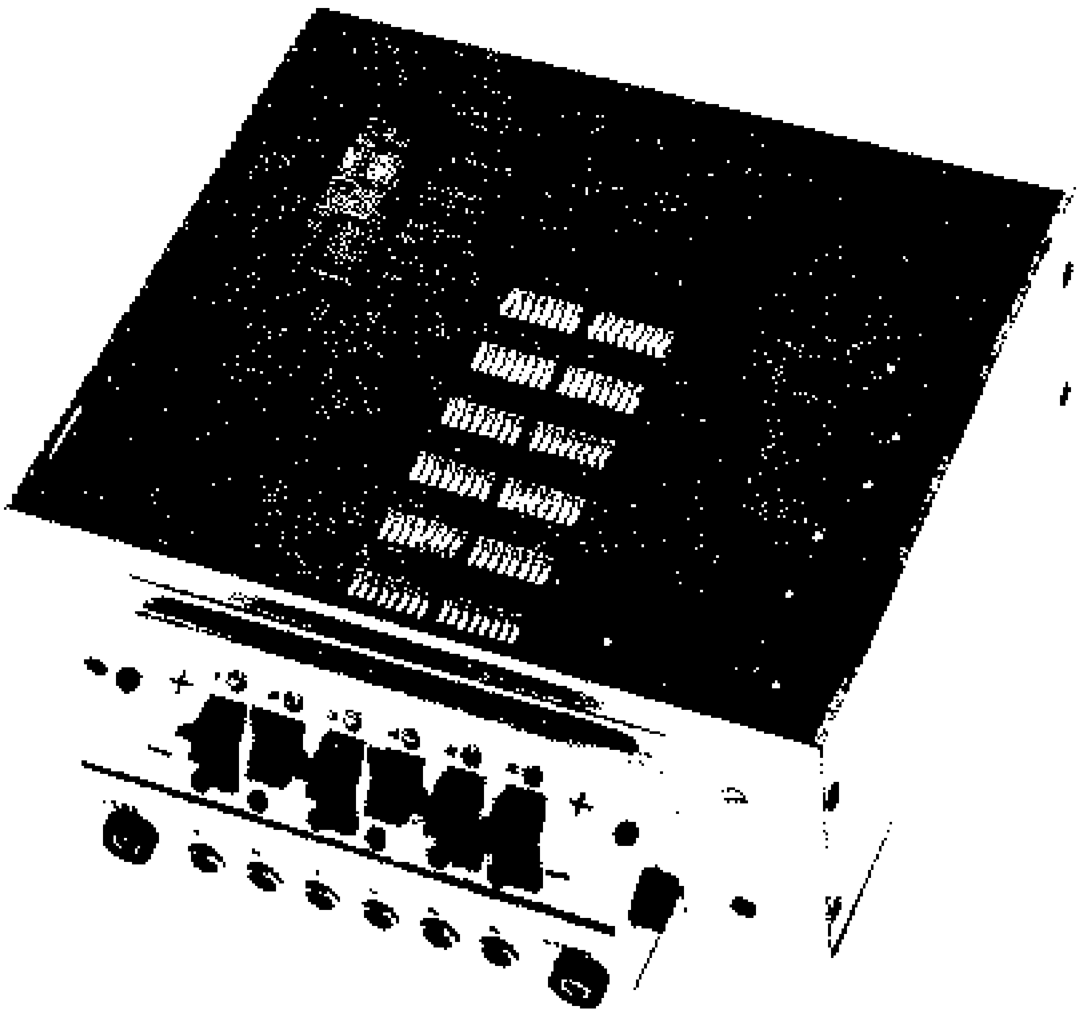

Fig. 1. Microprocessor controlled six channel functional electrical stimulator.

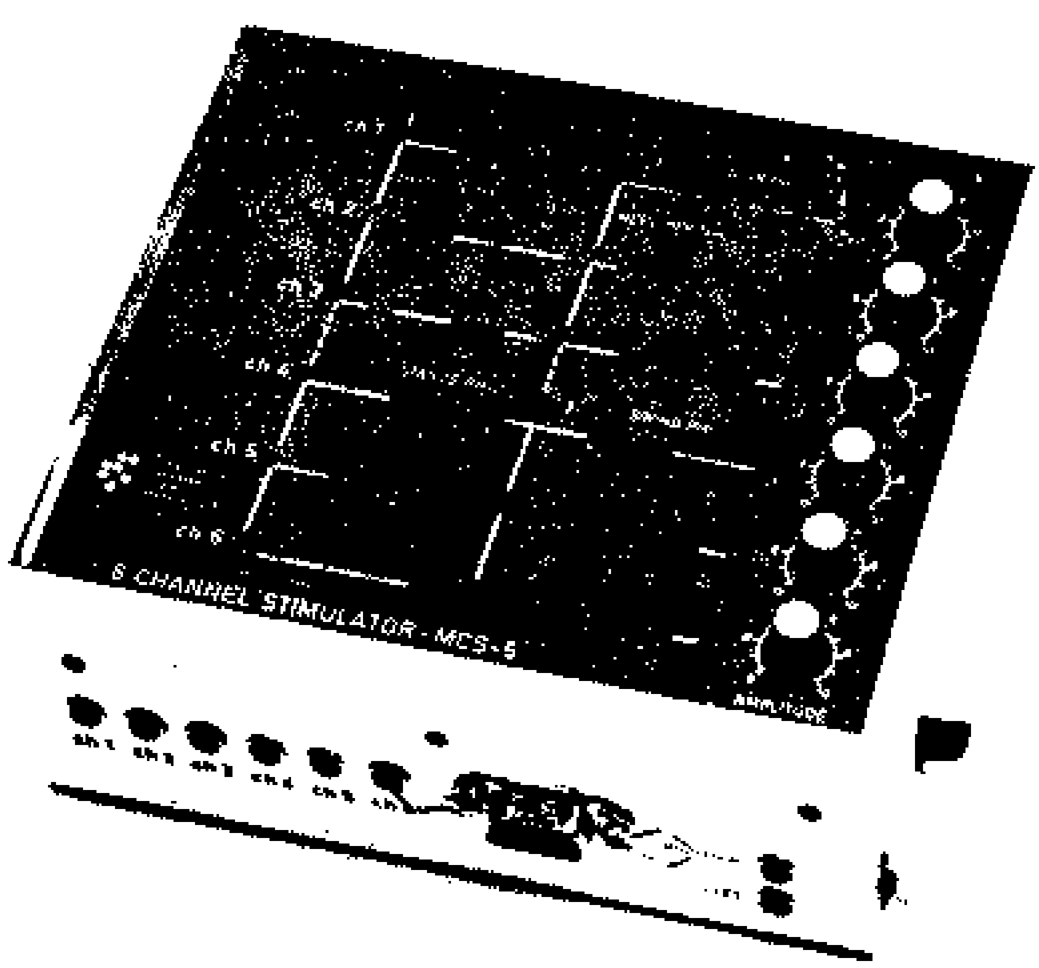

Fig. 2. MCS 5 - the most improved six channel "classical" functional electrical stimulator.

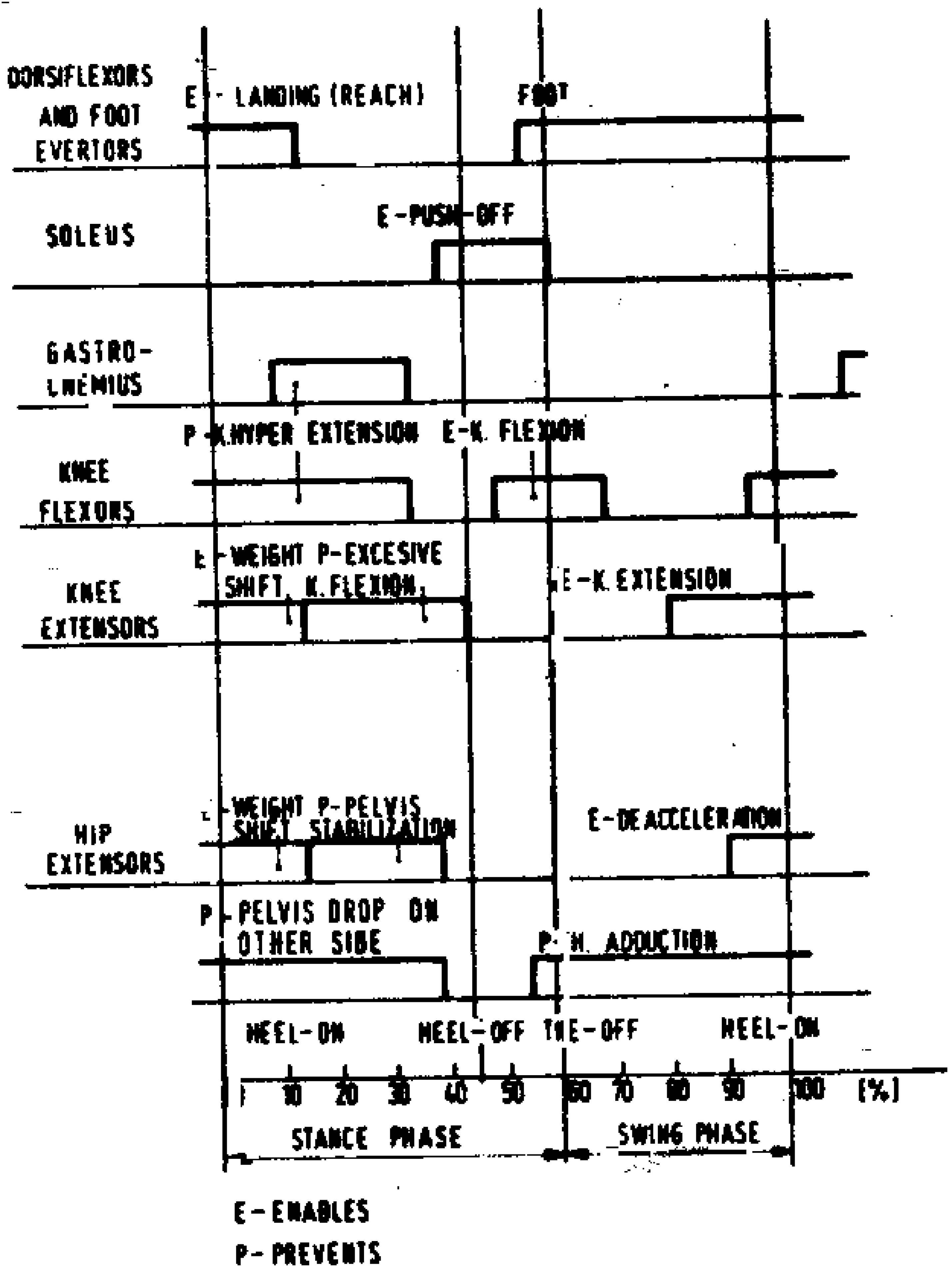

Fig. 3. General rules of multichannel stimulation sequence proposed for correction of typical hemiplegic gait anomalies.

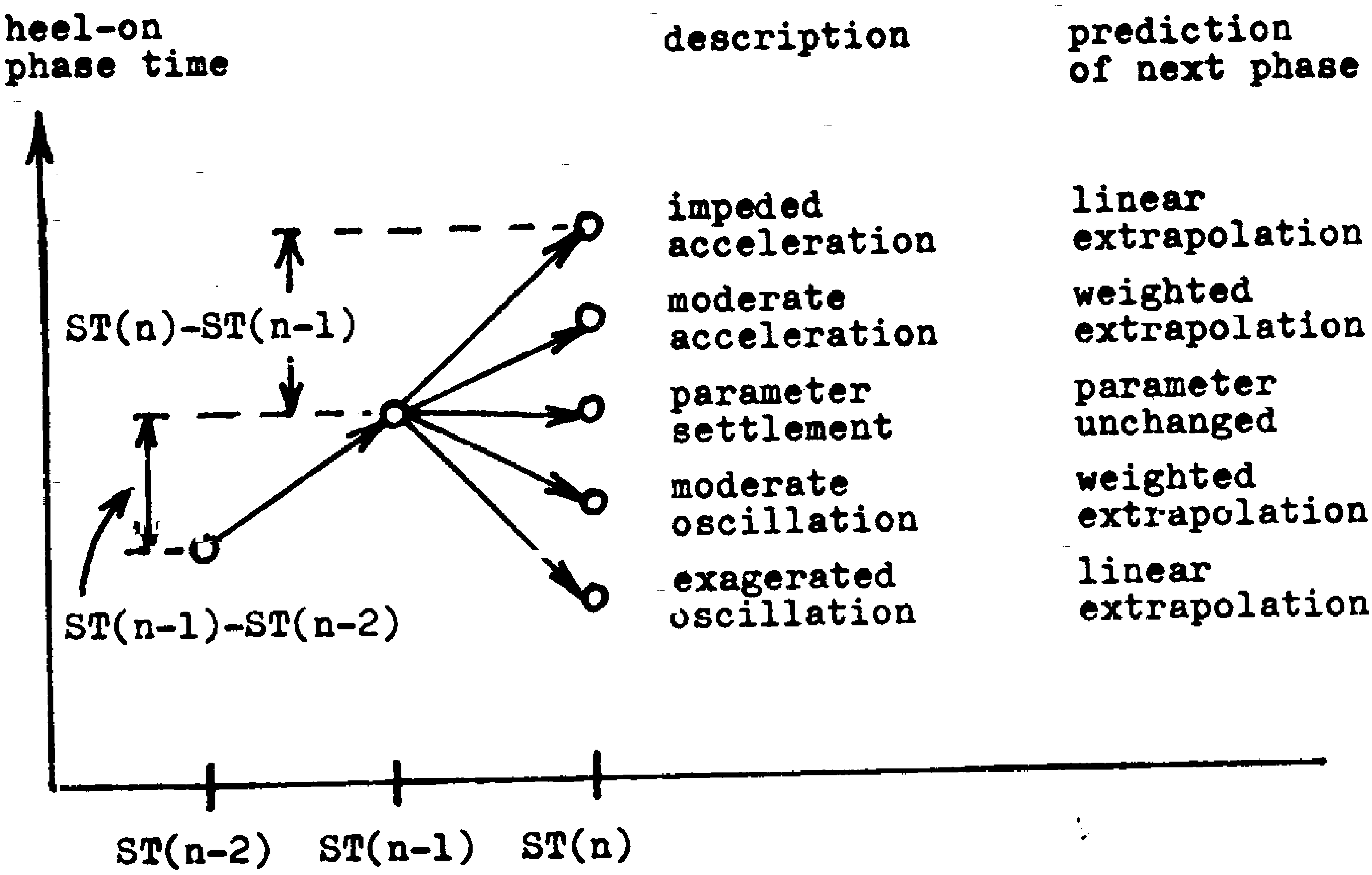

Fig. 4. Algorithm for prediction of the next gait phase.