DEVELOPMENT OF NEW SYSTEMS FOR FUNCTIONAL ELECTRICAL STIMULATION

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Summary

Application of electrical pulses to peripheral nerve trunk or to a muscle itself obviates the physiological protective mechanisms coupled with the lower motoneurone which results in obtaining rather crude movements. This form of stimulation termed efferent functional stimulation is used in hemiplegic patients for the control of paretic peroneal muscles and wrist extensors. Whenever the motor fibres are stimulated, spinal afferents are inevitably stimulated. In this way, the efferent FES of sufficient duration also gives rise to some kind of conditioning of motor reflex mechanisms, and changes their organization.

Lower simulation threshold of certain afferents and specific excitability of receptors offers the possibility of selective afferent stimulation with electrical or mechanical stimuli. Effects of such stimulation for example are the suppression of involuntary activity such as clonus in antagonists, augmentation of the existing minimal EMG activity in protagonists; these effects outlast the actual duration of stimulation.

The possibility of external control of excitation and inhibition by means of programmed afferent stimulation suggest that a system can be built which, incorporated into the physiological automatic regulation at the level of the spinal cord, could improve the voluntary control of movement.

First results in this field, as the Functional Electronic Radial Brace and the suggested anti-clonus model, are discussed.

In contemporary medicine, use of electrical stimulation for external control of movement is acquiring an increasing importance. Numerous systems have been advanced for experimental and practical purposes to control heart beat, contraction of urinary and anal sphincters, diaphragm, and paretic muscles of the extremities [1, 2, 3, 4]. All these systems have in common the application of electrical pulses to a peripheral nerve trunk or to a muscle itself with a view to obtaininig a direct motor response — contraction of the muscle. Therefore this is an external control at the level of the motor units. The stimulation applied in this way obviates the physiological protective mechanisms coupled with the lower

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motoneurone: the afferents from Golgi tendon organs and others. One of the consequences is that gradation of contraction in obtaining a smooth and skilled movement has largely remained an unsolved problem. The movements obtained are rather crude as compared to normal voluntary or reflex movements [5]. This form of stimulation has been termed efferent functional electrical stimulation (efferent FES) and it is used in hemiplegic patients for the control of paretic peroneal muscles during walk and of finger and wrist extensors for hand opening [6,7]. These are simple movements serving only as a component to more complicated movements; for this purpose this way of stimulation is satisfactory. This is even more so, because after some use of such stimulation, cyclical activation and inhibition of paretic muscles similar to the normal pattern becomes re-established and is evident even in the absence of stimulation. Clearly this could not be ascribed exclusively to the efferent effects (Figs. 1 and 2).

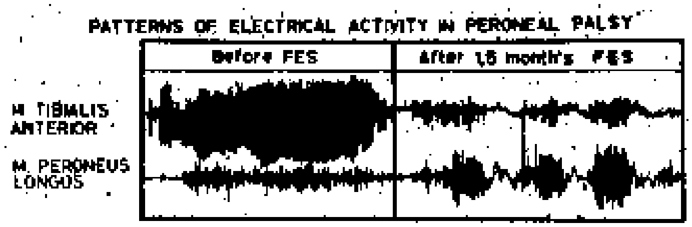

Fig. 1. An electromyographic record of the peroneal and anterior tibial muscles of a patient with foot drop due to cerebral stroke. The left half of the record was taken at walk after 6 months' corrective physiotherapy. The right half was recorded from the same muscles in the same conditions following 6 weeks of functional electrical stimulation of the peroneal nerve.

The spinal motoneurone, which is directly stimulated in efferent FES, has been termed "the final common pathway" because it is coupled not only with the cortical and subcortical structures but also with the spinal efferents, both mono- and polysynaptic. These spinal afferents are contained in the nerve trunk and are inevitably stimulated, whenever the motor fibres are stimulated.

So, in addition to direct motor effects, the efferent FES of sufficient duration gives rise to some kind of conditioning of motor reflex mechanisms, and changes their organization during walk.

However, the lower stimulation threshold of certain afferent fibres and specific excitability of receptors offers the possibility of selective afferent stimulation with electrical or mechanical stimuli (Fig. 3).

Studies of the effects of such stimulation in hemiplegic patients have shown the following:

1) It is possible to suppress involuntary activity such as clonus in antagonistic muscles, by careful selection of the para-

meters of the electrical stimulus [8]. In this way, clonus may eventually disappear completely (Fig. 4).

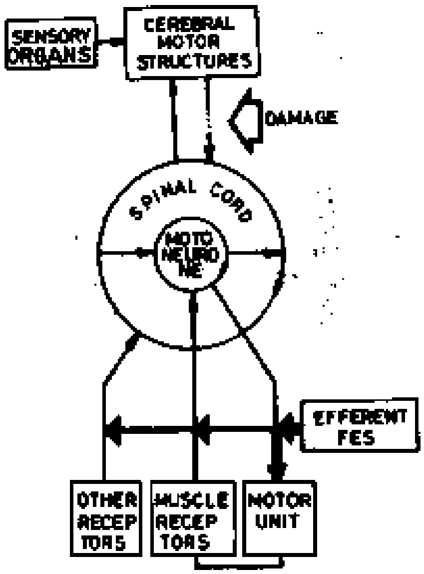

Fig. 2. Efferent FES not only directly activates the motor units, but also gives rise to a massive artificial sensory inflow directly and indirectly impinging upon the spinal motoneurone. This inflow has no evident effect upon the movement obtained, because the reflex responses are predominated by the direct (efferent) response. However, there are certain, not fully known effects of long-term use of such stimulation of spinal afferents, which include restoration of reciprocal patterns in automatic movements, such as gait.

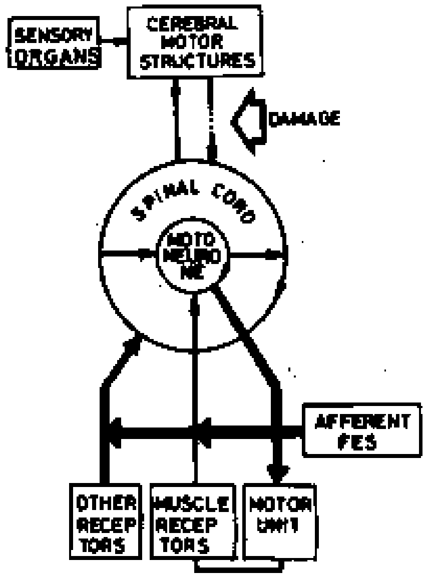

Fig. 3. Afferent FES activates the motoneurone indirectly, via the afferents. The movement obtained thus results from the activation of a variety of reflex and central mechanisms including the processes of facilitation and inhibition of different motoneurone pools.

2) Electrical stimulation subthreshold for motor nerve fibres can enhance the existing minimal EMG activity in protagonistic muscles [9] (Fig. 5).

3) Effects of afferent FES upon reflex motor activity both in protagonistic and antagonistic muscles outlast the actual duration of stimulation, sometimes for several seconds [10] (Fig. 6).

In patients with an upper motoneurone lesion, the lower motoneurone, i.e. the final common pathway, does not receive enough information to initiate and complete a movement, which results in paresis or paralysis of one or more limbs. This, however, does not only imply the absence of voluntary power but also an inadequate control of muscle tone, uncontrollable spontaneous

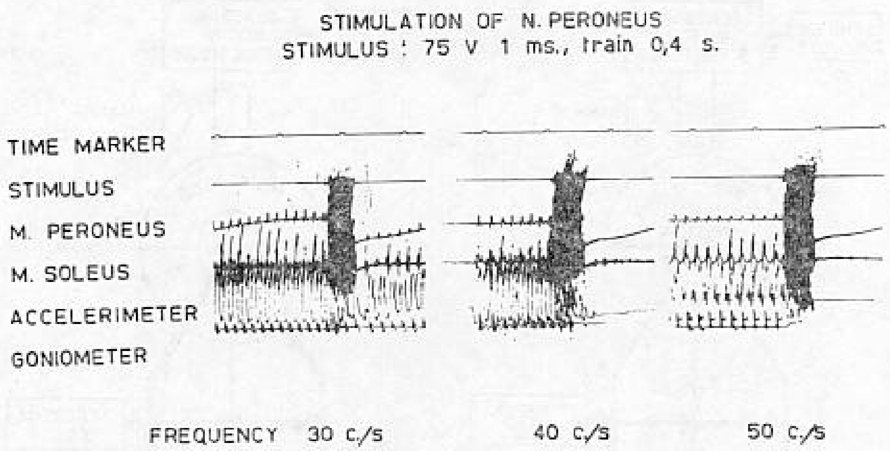

Fig. 4. Dependency of the anti-clonus effect upon frequency of the stimuli within the train. This proves that the effect of stimulation is highly specific.

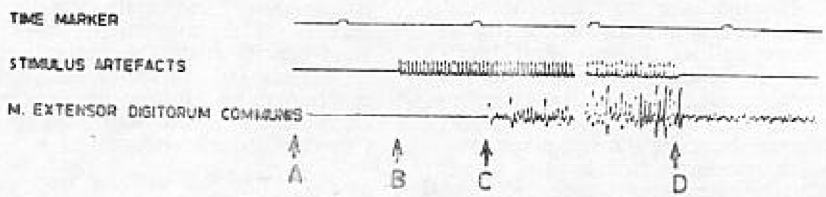

Fig. 5. Electromyographic record of the extensor digitorum communis in a patient with drop wrist due to cerebral stroke. In A, patient was asked to extend his wrist. EMG silence means that patient is incapable of volitional control of this muscle. At B, train of electrical stimuli applied to radial nerve above elbow. The absence of EMG activity proves that the applied stimulation was pure afferent. At C, the patient was again asked to perform voluntary extension of the wrist, while stimulation was continued. He succeeds; this produces an EMG response in the muscle. At D, voluntary effort of the patient is continued but stimulation is discontinued. There is an immediate break of EMG activity, with persistence of some small amplitude action potentials insufficient to produce a movement.

movements, and impaired reciprocal innervation due to derangement of spinal reflex systems. These phenomena represent a major obstacle to purposeful use of the remaining voluntary control, which is already insufficient in itself.

The possibility to externally controlled excitation and inhibition, which are needed in any movement, by means of programmed afferent stimulation, opens a new approach: to build a system which would incorporate itself into the physiological automatic regulation at the level of the spinal cord, or the motor reflex integration. This should improve the voluntary control both of automatic movements, such as walk, and of other purposeful movements.

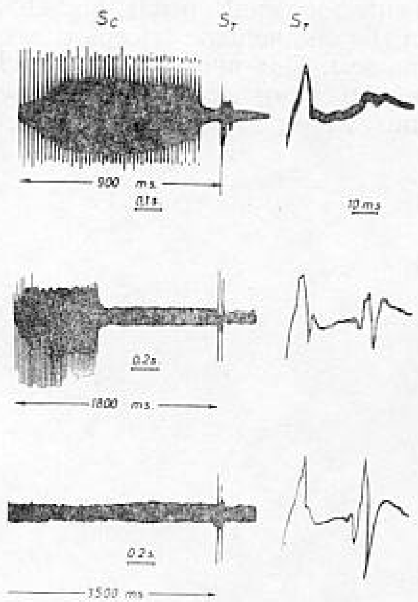

Fig. 6. Stimulation of the peroneal nerve with a conditioning train produced a depression of the H-reflex outlasting the conditioning stimulus for more than 3 seconds.

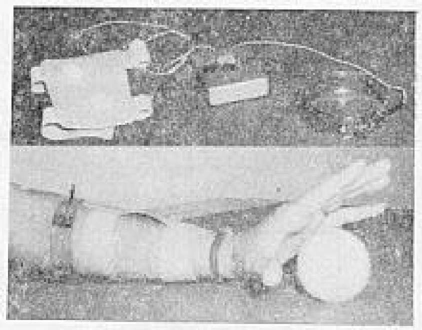

Fig. 7. Functional Electronic Radial Brace.

We wish to present some of the first results of such systems without discussing the details of engineering problems, theory, methodology, or technology.

Our Functional Electronic Radial Brace (Fig. 7) may serve as a successful example of the afferent FES used to facilitate voluntary control of extension of the wrist and fingers in patients with hemiparesis [11].

As is known, the difficulty in performing these movements is mainly due to excessive hypertonus in the antagonistic flexor muscles. Repetitive FES of the radial nerve or its terminals in motor points of individual muscles tends to decrease the flexor tone to such an extent that the patient is able to use his hand for less demanding motor tasks.

In this way, the afferent FES not only enhanced the pre-existent minimal voluntary activity in the stimulated muscles, but also inhibited the antagonistic muscles at the same time decreasing their tone and suppressing involuntary contractions.

Another example of externally controlled inhibition by FES is suppression of clonus. The peroneal nerve is stimulated by a train of stimuli above the threshold for monosynaptic reflex response. Sustained activity in the monosynaptic reflex are results in a weak tonic contraction of the anterior tibial muscle, and this gives rise to reciprocal inhibition in the antagonistic triceps surae, which stops clonic activity in this muscle. This phenomenon could be used for the construction of an anti-clonus device to improve rehabilitation of patients with clonus, as we have suggested elsewhere [12] (Fig. 8).

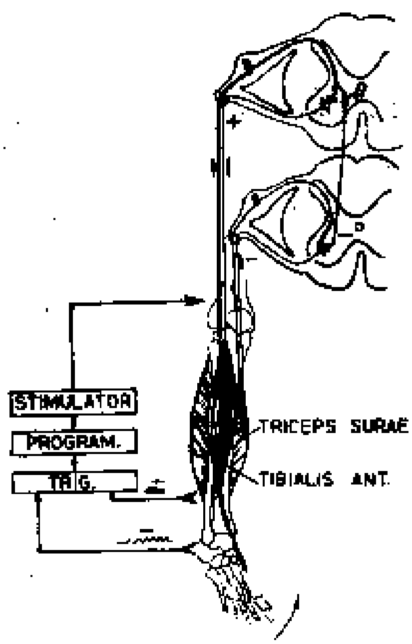

Fig. 8. Anti-clonus model. Clonus in triceps surae (detected by electromechanical or bioelectrical clonus detector) triggers stimulator, which delivers stimuli to afferent fibres of peroneal nerve. These evoke slight contraction in the tibialis anterior muscle, and at the same time inhibit clonic activity in antagonistic triceps surae muscle.

Now underway are the studies on multi-channel stimulation for the control of more complex and precise movements. By careful choice of the sites of stimulation and fine adjustment of stimulus parameters we expect to more succesfully control the relationship between peripheral and central events important for motor reflex integration and the organization of movement. Surface stimulation will undoubtedly not suffice and implants will contribute to the final solution of this problem. However, before such aids can be given to the patients, careful and extensive studies are needed to achieve an optimum efficiency and to minimize the possibility of untoward side effects. For it must be borne in mind that we are only at the beginning of the external control of movement by means of programmed afferent inflow.

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