FUNCTIONAL STIMULATION

FURTHER ADVANCES IN USE OF PHYSIOLOGICAL MECHANISMS IN THE EXTERNAL CONTROL OF HUMAN EXTREMITIES

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Summary

Neurophysiological aspect of organization of movement in man and possibilities of restoring the impaired motor function of human limbs by means of external electrical control are discussed.

First, some results of the research activity in the past three years are reviewed the aim of which was to provide a neurophysiological background for the design of new systems for the improvement of movement in patients with a lesion of the central nervous system. Second, neurophysiological problems of controlling signals of neuromuscular and cerebral origin are discussed. Third, a report is given of some new results of the studies of motor organization of the human spinal cord in paraplegia, and their significance for external control of human extremities is discussed.

The neurophysiological basis of normal and pathological motor activity in man is still poorly understood, but significant progress is made year by year. Neurologists, psychiatrists and research workers interested in this field propose, with an ever increasing number, new, ingenious, and refined experimental techniques applicable to the research problems of the organization of movement. On the other hand, their work is continuously stimulated by the progress in animal research and by the increasingly promising development of biomedical engineering.

In this report, I wish to bring to your attention the following three topics:

1. I would like to review some of the results of our research activity in the past three years, which was to provide a neurophysiological background for the design of new systems for the improvement of movement in patients with a lesion of the central nervous system.

2. I wish to discuss some neurophysiological problems of controlling signals of the neuromuscular and cerebral origin.

3. I will report on some new results of our studies of motor organization of the human spinal cord in paraplegia and discuss their significance for external control of human extremities.

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Electronic Braces for Externally Controlled Movement by Functional Electrical Stimulation

After our first successful attempts to improve locomotion of hemiplegic patients with foot drop by means of electrical stimulation of the peroneal nerve [1], we tried to analyse the effects of this method by means of some neurophysiological technique. The preliminary observations were reported in Dubrovnik and Prague [2, 3, 4]. The conclusion resulting from these observations was that in electrical control of paralysed muscles we do not only operate muscles but also influence the nervous system [3]. Having this in mind we defined two essentially different approaches in functional electrical stimulation (FES): *efferent* and *afferent* FES [5]. The former is stimulating the peripheral motor nerves of the paralysed muscle to evoke its contraction. The latter is stimulation of the afferent, i.e. sensory limb of the spinal reflex arcs — oligosynaptic and polysynaptic ones (Fig. 1).

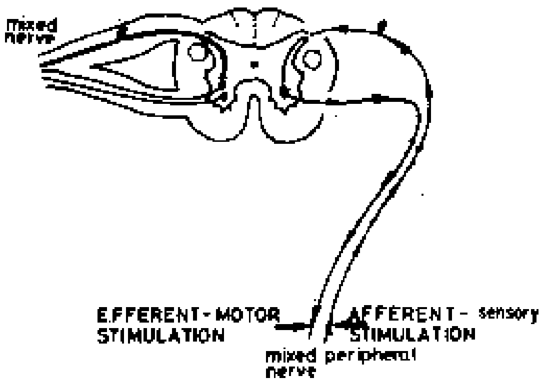

Fig. 1.

The afferent FES is being developed by our group with the purpose of making use of the preserved spinal reflex motor integration and in this way to support the insufficient supraspinal control.

Following this concept, we have directed our research along two main lines:
firstly, apart from studying external control of excitation, we started a search for the possibilities of externally controlling facilitation of excitation, facilitation of inhibition and inhibition itself;
secondly, we tried to identify and elucidate the acute and chronic effects of electrical stimulation such as is used in the Ljubljana Functional Electronic Peroneal Brace, upon the neurophysiological organization of movement in hemiplegia.

We have succeeded in the attempts to externally control facilitation of excitation and facilitation of inhibition [6], and we obtained a very active inhibition itself [7, 8].

The possibility of externally facilitating excitation encouraged us to design a new device supporting extension of wrist and fingers in patients with wrist drop. Gračanin will report on some details and theoretical and practical implications of this device.

Concerning the acute and long-term effects of FES, we reported on the latter on the International Meeting on Electromyography in Glasgow, in 1967 [9] and at the 5th International Congress of Physical Medicine in Montreal in 1968 we discussed the immediate influence on spinal reflex activity of the tetanic stimulus such as is used in the Ljubljana Functional Electronic Peroneal Brace [10]. We have seen that this stimulus evokes a profound and long-lating depression of excitability in the motoneurone pool of the peroneal and tibial nerve. This is in agreement with observations of Gračanin and Grobelnik that were made in 42 patients who were using the Ljubljana Functional Electronic Peroneal Brace for prolonged inhibition of the stimulated muscles and their antagonists during periods of time: in these patients, the normal cyclical activation and gait were re-established, as they reported on the symposium on Electronics in Medicine in Ljubljana a year ago. These two observations prove that the Ljubljana Functional Electronic Peroneal Brace not only effectively controls foot drop during gait, but is also very potent in reorganization of the impaired motor functions of the spinal cord.

Another important conclusion arising from these studies was that hemiplegics with equal clinical signs and motor defects may have very different underlying neurophysiological disturbances of the motor mechanisms [11]. Thus we have realized the need for categorization of hemiplegic patients based on the neurophysiological nature of their motor derangement. We are trying to do this by some newly introduced neurophysiological methods [12]. Some preliminary results will be reported this year [13].

In this review I have ignored many important results of other researches obtained in man and animals, in normal and pathological conditions. This was on purpose because these results have already been reviewed elsewhere [14, 15] and my intention is to deal only with studies closely related to the problems of FES.

However, I would like to mention a very recent report coming from the Philips Research Laboratories and the University of Technology in Endhoven [16] concerning the use of a functional peroneal brace in hemiplegic patients. A few months ago we found another similar report by California investigators [17] and our own observations [2, 3]. In the near future we may expect such reports from other medical centres, describing perhaps new technical solutions and it may well happen that by the next Symposium in Dubrovnik we shall have a whole series of different peroneal braces with different names, different performances, and different results. The workers of our own group are trying to improve the already commercially available Ljubljana Functional Electronic Peroneal Brace, [18].

Finally, I must mention the work of Hufschmidt, who developed a method of electrical stimulation of muscles to reduce spasticity. We have no personal experience with this method, but we are certain that it represents a new and valuable approach in the treatment of spasticity [19].

The progress of FES in clinical use opens another problem common to orthotics and prosthetics, that of the controlling signals and of the controlling site. For this reason, we have devoted some attention to the neurophysiological aspects of controlling signals of neuromuscular and cerebral origin. I will try to inform you briefly of our preliminary results in this field.

Some Neurophysiological Problems of Controlling Signals of Neuromuscular and Cerebral Origin

The use of motor action potentials as detected by superficial electrodes for myoelectrical control has many advocates in prosthetics, and certainly did prove to be a valuable source of controlling signals. Perhaps it will find even wider application in the future when we may be able to derive more information from the EMG signal by suitable time and amplitude analysis.

In the last two years we gained some experience with detection of single muscle fibre action potentials using the method described by Ekstedt and Stålberg [20, 21]. The advantage of these signals is their all-or-none appearance and the possibility of frequency adjustment. From the work of Trontelj in our Institute it follows that selective voluntary control of single fibres is possible, but is not quite simple [22].

One of disadvantages which will probably complicate the use of these signals is the existence of physiological differences between muscle fibres. The tonic and phasic fibres and the transitional types between these two extremes are characterized by different innervation and frequency patterns. Furthermore, human muscles contain all the types intermingled and in varying proportions. Another disadvantage is that the selective recording from single fibres demands very slight activation of the muscle to avoid disturbing potentials from neighbouring motor units. Large changes in the voluntary effort that the latter may be imperceptible for the subject. For it must be borne in mind that there exists no sensory clue to identification of individual motor units.

So, one would expect that only a few muscles could prove suitable as a source of such a signal.

The so-called gross electromyography signals have less disadvantages; at least tension felt in the contracted muscle provides a better reference for the quantity of EMG energy generated.

Reports on contingent negative variation by Walter [23] and other investigators have drawn our attention to the possibility of using this biopotential of cerebral origin as a controlling signal. As you will hear in the report by Lokar and co-authors, it indeed proved possible to train subjects to generate this potential at their will without there being needed any movement of any muscle of the body. This offers a very interesting and promising possibility of communicating with a patient unable to move any of his skeletal muscles, which has so far been completely impossible.

Some Features of Spinal Motor Organization in Paraplegics of Importance for the External Control of Movement by Functional Stimulation

The paraplegics (Fig. 2) represent another large group of patients unable to walk normally. Their problems, however, are completely different from those of hemiplegics — not only from the standpoint of biomechanics of locomotion but also from the standpoint of neurophysiological derangement. In the case of hemiplegia, the lesion is high up in the central nervous system: it is located in the brain and is unilateral. In paraplegia, it can be at any level of the cervical or thoracic spinal cord, or it may be lower

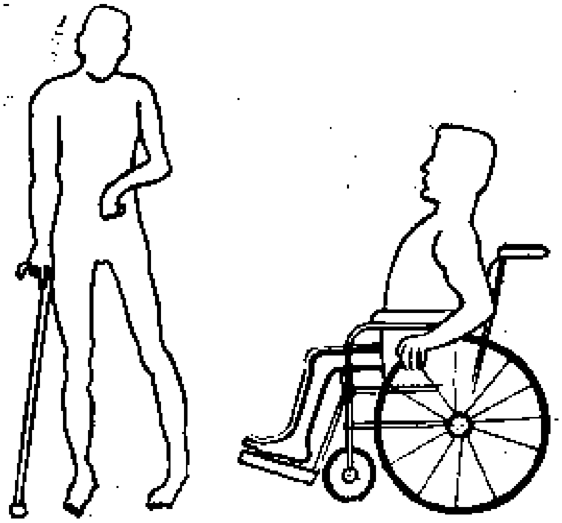

Fig. 2.

than that with the involvement of roots of spinal nerves. I will not discuss this latter case, which, being a lower motoneurone lesion, is again a completely different condition.

In the former case, there is a longer or shorter stump of the spinal cord, partially or completely divided from the rest of the central nervous system, but with intact afferent and efferent, i. e. sensory and motor, connections from the periphery. The stump thus receives the whole information from the periphery, and when the division is complete, it also independently governs the motor activity of its part of the body (Fig. 3).

This spinal governor and its activity resulting in the features of spasticity has been one of the main subjects of our research work for the last seven years. Some of the results of this work, which is being carried out in collaboration with W. Nathan of the National Hospital for Nervous Diseases in London, have been reviewed on the preceding Symposium in Dubrovnik. From the studies of oligosynaptic and propriospinal polysynaptic pathways followed that in the normal condition, the function of the spinal interneuronal system is to supersede the primitive segmental organization.

Thus it is this system which, being interposed between the primary sensory neurones and the lower motoneurones, is, at the spinal level, responsible for the initiation of complicated movements.

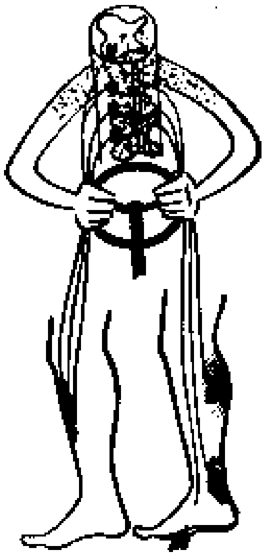
Fig. 3.

When we realized that this system is very active in spinal spasticity in man and that it probably accounts for the "chaotic motor activity of paralysed limbs", we asked ourselves the following question: Is this chaotic overactivity, which can be made more regular during tendon jerk activation, related to this kind of stimulation? We may presume that the loss of supraspinal control also involves a loss of supraspinal mechanisms modifying the afferent inflow. If this is so, then we could hope to obtain higher organized and even functional movements if we regulate the afferent inflow by applying properly patterned stimulation.

So, instead of electrical stimulation of muscles, we propose programmed stimulation of spinal afferents, to re-activate the spinal reflex integration mechanisms and so to substitute for the missing supraspinal modification of the afferent inflow. This could probably re-build at least some simple motor patterns and perhaps even help the paraplegic to walk.

Therefore we decided to study different kinds of stimulation and the resulting patterns of the afferent volleys, with the view to correlating them with their effects upon the spinal mechanisms.

For this purpose we introduced the technique of intraneural detection of sensory action potentials developed by Hagbarth and Vallbo [24]. The recording on Figure 4 shows the sensory volley produced by a sharp tap on the skin: the discharge lasts considerably longer than the actual stimulus.

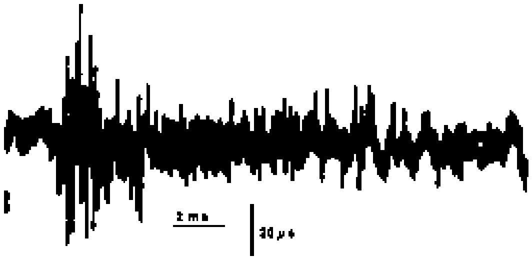

Fig. 4.

We have approached the problem of physiological standardization of the various types of stimuli for exploration of the interneuronal system also from the other side: we introduced the detection of somatosensory evoked responses from the scalp over the postcentral gyrus, using the averaging technique. Comparison of electrical and mechanical stimulation has shown that, for obtaining a response, it is not so important to use only short stimuli producing sharp-fronted volleys, as has been hitherto assumed.

The left side of Figure 5 shows compound action potentials detected over the median nerve after electrical stimulation of digital nerves, after a tap to a fingernail, and after a tap to the thenar. The right side shows the corresponding cerebral evoked potentials. It can be seen that a sharp and brief afferent volley gives rise to a complex, long-lasting cerebral evoked potential, and a temporally dispersed volley evokes a similar cerebral response of equal duration. One of the important functions of receptors therefore seems to be temporal dispersion of the effects of short stimuli, while the central nervous system re-synchronizes this information (Fig. 6).

On the basis of these studies we decided to use a tetanic electrical stimulus giving rise to a sharp and well synchronized pain as a basic stimulus for our studies of the interneuronal system.

The complex stimulation needed in these studies necessitated the construction of a new dual-channel stimulator, which offers great versatility of stimulus parameters, as well as the possibility of programming varied patterns and of a feedback control [25, 26].

Our basic painful stimulus I mentioned above is a train of rectangular pulses 0.2 msec. wide and repeated at 2000 cycles per second. The duration of the train is 20 msec.

The application of this electrically simulated painful stimulus to the plantar surface evokes a complicated motor response of the whole limb which tends to withdraw the foot from the stimulus. This response is known as flexor reflex.

The response obtained is determined by intesity of stimulation (which, of course, is not painful if the division of the cord is complete), by the presence or absence of motor unit activity at the time of stimulation, by the position of the limb and the phase of movement of the limb, if it is moving or being moved.

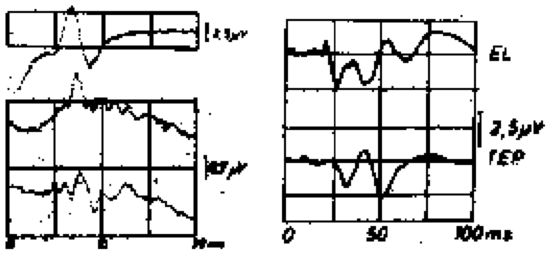

Fig. 5.

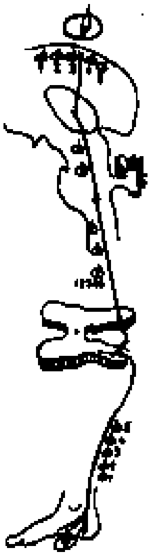

Fig. 6.

However, even when the limb is at rest, responses to a series of stimuli can vary quite a lot. In typical cases, there was an initial increment of the responses to consecutive stimuli, which was then followed by a progressive decline in the overall amount of the evoked activity. Latencies, number of muscles involved, duration and amplitude of the responses and even the patterns of muscles activated varied concomitantly (Fig. 7).

After we saw how greatly the responses to constant cutaneous noxious stimulation vary in most of their parameters even if the position of the limb is kept constant, we felt that it was necessary to study the consistency of responsiveness in the particular spinal pathways.

In our studies of changes of the flexion reflex with repetitive stimulation in spinal man [27, 28] and of features affecting the habituation of this reflex [29] we have worked out how frequently a minimal noxious stimulus has to be applied to be responded by the spinal cord. The response to a noxious stimulus well above threshold applied repetitively passes through the following phases:

build-up, constancy, fluctuation, diminution, and absence of the response (Fig. 8). The faster the stimulation rate and the stronger the stimulus, the sooner each phase is reached. These phases do not occur simultaneously in all muscles. When repeated stimulation at one site has brought the responding motor units to the phase of absence of response, the response can be restored by stimuli of the same or other kind applied anywhere else in the limb (Fig. 9).

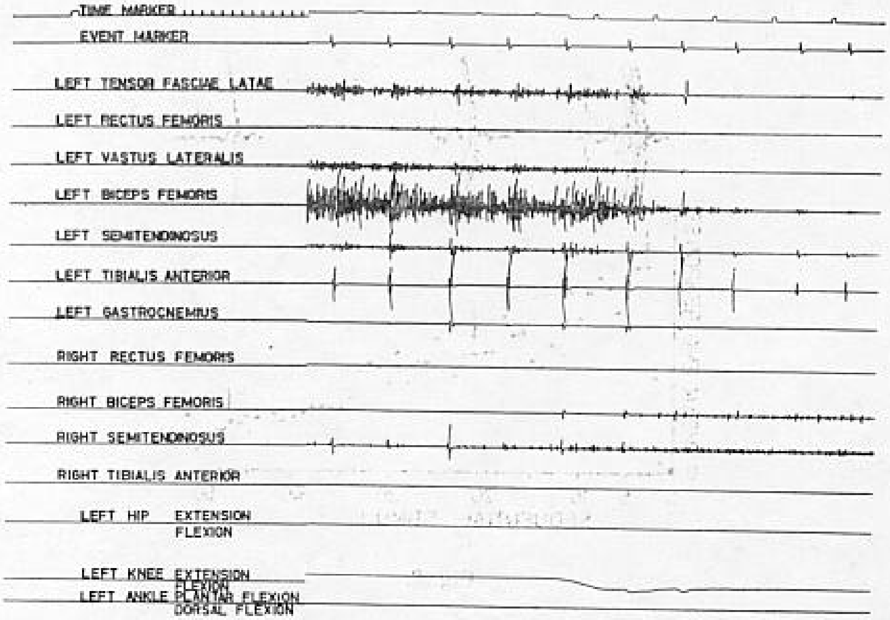

Fig. 7.

The site from which the activity can be restored can be as near as 4 cm. from the first site. Stimulation of the same of different kinds applied to the contralateral limb also restores the response of these motor units. But in all cases the restoration of activity is evanescent. Repetitive stimulation at the second site soon evokes no response from these motor units; this phase is reached much sooner than it would have been had the first site not already been brought to this phase before.

The finding that rhythmic and regular cutaneous noxious stimulation in these patients produces habituation demonstrates that the interneuronal system of the spinal stump is still capable to control and suppresses the effects of the afferent inflow and thus to decrease the state of excitation.

To elucidate the function of habituation in more detail, stimulation was made random either in frequency or in amplitude. The stimulator [25, 26] was controlled by a computer generating a stochastic function. Such stimulation could prevent or at least delay the development of habituation. Habituation was even more successfully prevented by the feedback loop controlling the amplitude of stimulation: decreases in the mean quantity of EMG response [30] were compensated by increase in amplitude and vice versa (Fig. 10). Habituation did not appear, although the average strength of stimulation was even less than with regular stimulation which produced rapid habituation.

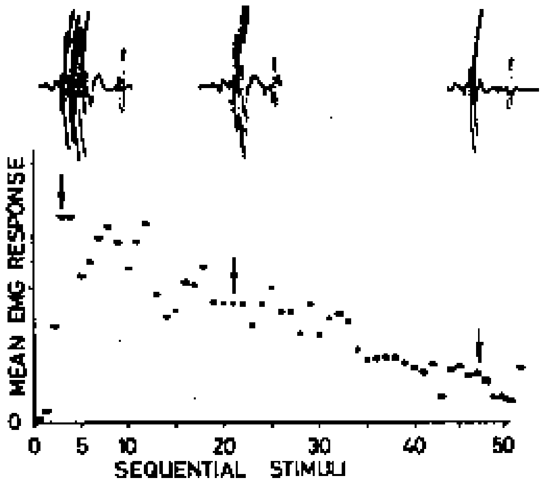

Fig. 8.

So far we have arrived with our research in motor function of the isolated human spinal cord. Our findings have furnished an increasing evidence that from the so-called "chaotic state" definite patterns may nevertheless emerge if we are using properly patterned stimulation. The conclusion would then be that even in complete paraplegia some kind of a complicated motor organization does exist and that it can even be reorganized provided that we properly control the inflow to the spinal cord.

So all this seems encouraging as regards external control of excitation and of facilitation of excitation. But an equally important requirement of functional movement is depression of excitation and inhibition. We must not only be able to actively start a movement, but also to actively stop it. We are considering the possibilities of externally controlling inhibition. This, however, is in a rather preliminary phase.

At this stage it would seem that we shall meet many problems, both neurophysiological and engineering, before we are able to give a paraplegic patient a device helping him to walk by functional electrical stimulation.

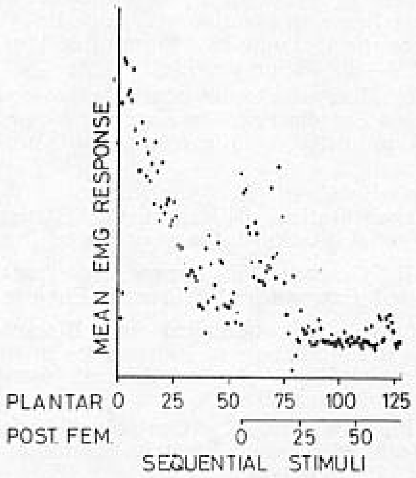

Fig. 9.

To conclude, I believe that you will agree that in the 3 years since the 2nd Symposium on External Control of Human Extremities has become an even more fruitful field for creative interdisciplinary collaboration between engineers and physicians, mathematians and physiologists, and other research workers. This collaboration not only promises to give new devices and rehabilitation procedures to disabled people but also to advance our knowledge of human organs subserving movement.

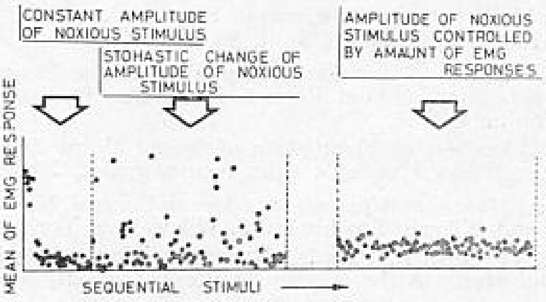

Fig. 10.

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