FES ASSISTED MANIPULATION IN QUADRIPLEGIC PATIENTS

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Summary

Fifteen complete quadriplegic patients with C-4 to C-7 spinal cord lesions have participated in testing the effects of the surface electrical stimulation on the paralyzed forearm muscles. The results obtained show that it is possible to generate appropriate prehension and release in almost half of them.

Three patients were supplied with stimulators where potentiometer position control was implemented. The stimulator is fixed on the wheel-chair under the arm support. One of the affected arms controlling the potentiometer is providing grasp and release to the other affected hand. With such an orthosis it is possible to manipulate with different objects and strengthen the muscles involved. The results of measurements on one quadriplegic patient (C-5) have shown an increase of the muscle force while no therapeutic effects have been noticed.

The problems concerning the application of different surface electrodes to quadriplegic patients muscles are discussed.

I. Introduction

In Ljubljana Rehabilitation Engineering Center the application of functional electrical stimulation (FES) of upper extremities was mostly intended for hemiplegic patients /1/. With quadriplegic patients electrical stimulation was used as therapeutical method only as it seemed rather difficult to obtain functional movements by surface stimulation /2/. Because of the car and sport accidents the number of quadriplegics is constantly increasing. After the spinal cord injury the lesions from C4-C7 hinder many of important functional movements of the hands. Restoration of any movement means a significant step to better quality of life and lesser extent of dependence on other people. The first preliminary experiments with transcutaneous FES have shown that it is possible to realize an appropriate prehension and release.

II. Patients' screening

A systematic screening of quadriplegic patients has been undertaken in 1.8 millions of inhabitants of republic of Slovenia. Among 150 registered patients 13 were chosen for measurements at their homes having lesions between C4-C6 (Table 1). Muscular status test of finger and wrist muscles was performed to find out to what extent FES was required to improve the hand functions. Finger and wrist extension and flexion were produced by FES without patients voluntary contribution. The contraction levels of the particular muscle groups were denoted with the following grades: 0 - without response, 1 - poor contraction,

2 - partial movement, 3 - complete movement.

TABLE 1

INITIALS	SEX	YEARS	LESION	TIME AFTER INJURY
1. L.Z.	F	25	C7 accident	4 years
2. D.L.	M	36	C5 "	4 "
3. M.K.	F	37	C4-C5 "	2 "
4. V.K.	M	31	C5 "	3 "
5. S.Z.	M	29	C4-C5 "	9 "
6. M.B.	M	28	C5-C6 "	2 "
7. P.I.	M	32	C6 "	3 "
8. J.O.	M	38	C4 "	3 "
9. L.B.	M	42	C5 "	22 "
10. D.B.	M	27	C7 "	4 "

When comparing the voluntarily controlled movements with those produced by FES the same type of muscular status estimation was used. The parameters of stimulation varied from patient to patient in range from 20 V to 100 V. The frequency of FES was 30 Hz while the pulse duration was chosen between 0.3 to 2.5 ms. The results of the measurements performed during the patients screening are shown in Fig. 1. The vectors are

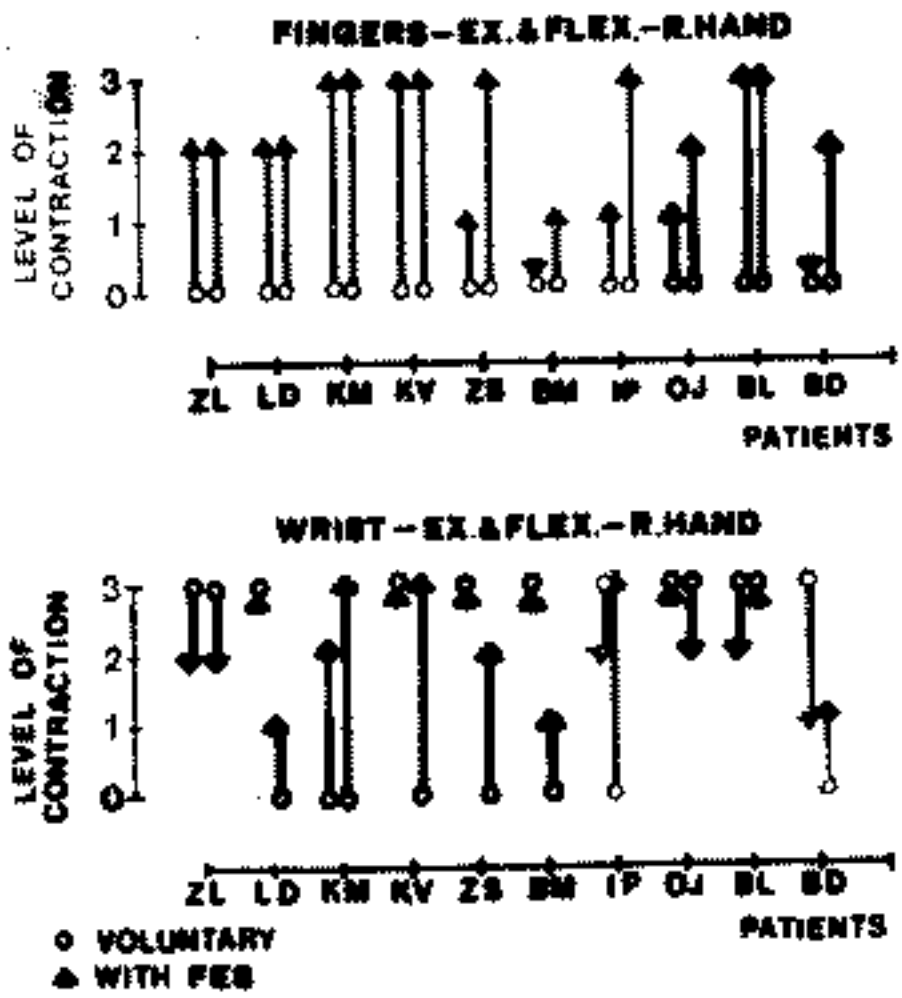

Fig. 1. Results of patients' screening

presenting the difference between the level of voluntary muscle contraction (starting point of the vector) and the contraction produced by electrical stimuli (end of the vector). From the diagram (1a) representing extensions and flexions of right hand fingers it is evident that none of the patients had voluntary control and that wrist extensors and flexors are only partially paralyzed. It can be also noticed that electrical stimulation can improve muscle contraction in most cases.

III. Stimulator

Based on these results it was concluded that FES orthosis would be a helpful tool of quadriplegic patients while manipulating and handling different objects. To control such an orthotic system natural control or learned control can be used /3/. In our case the learned control was chosen with one exception. The control signals are not taken from the unaffected part of the body. One arm was therefore sacrified as the source of the signals, which are controlling the grasp and release of patient's partially paralyzed other hand. This is possible because all complete quadriplegics with the lesions from C4 to C7 are able to control their shoulders and have preserved some movements in the elbows. These movements can be used to generate the control signals. In Fig. 2 control principles for activating finger flexors and extensors are schematically presented. The stimulator is proportionally controlled by the linear sliding potentiometer. As grasp and release never occur at the same time, one stimulation channel can be used for agonist and antagonist muscle group.

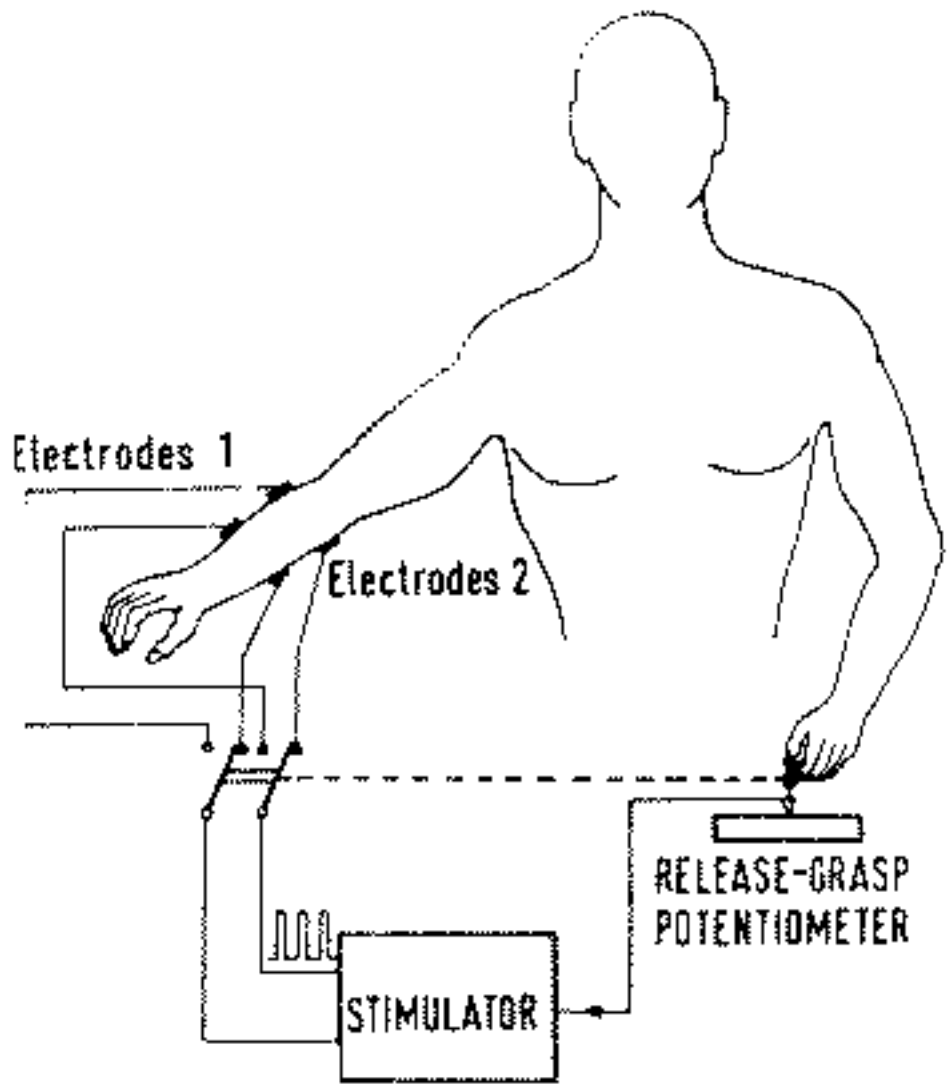

Fig. 2. Proportional control of complete quadriplegic patient's hand

A shift of the potentiometer slider left from the central position results in a train of rectangular stimulation pulses, whose amplitude is proportional to the shift. Electrical stimulation is led to the first pair of surface electrodes (Electrodes 1) providing the opening of the another hand. When returning the slider towards the central position the stimulation amplitude is decreasing. Passing the central position the stimulation is switched to the second pair of electrodes (Electrodes 2) from finger extensors to flexors, performing thus the closing of the hand. Visual feedback helps to get appropriate and precise finger movements.

The described principle was successfully used in the design of three stimulators which have been given to three quadriplegic patients: H.S. (C5-6 lesion), V.K. (C5) and K.F (C7). One of them is shown in Fig. 3 when controlling his right hand with the left arm. The stimulator with the sliding potentiometer is attached to the armrest of the wheel-chair. Surface electrodes are mounted to the extremity by four velcro straps. The second potentiometer is determining the slope of increasing stimulation amplitude. When stimulating finger flexors and extensors the wrist muscles are excited as well. Finger opening is therefore accompanied by wrist extension what makes the movement even more functional. The patient is shifting the potentiometer by the whole arm. He is touching it by his palm. All three stimulators are at patients' houses at present.

Fig. 3. Hand release (left) and grasp (right) with the help of proportionally controlled electrical stimulator

IV. Testing and strengthening program

When testing the FES orthosis the patients were asked to lift, carry and place different, specially designed small weights (0.05 to 0,5 kg) into the appropriate hollows (Fig.4). No one of them was able to perform the exercise without stimulation. The time needed to finish the task was registered during three weeks of training for patient V.K. with C5 lesion.

Fig. 4. Manipulation test with different weights

Daily stimulation of previously mentioned muscle groups improved the muscle strenght. Special therapeutical strengthening program was applied to the same complete quadriplegic patient . In the period of two months wrist extensors and flexors were daily stimulated. Before the treatment muscular status test has been performed for left hand. Voluntary activity was estimated with 0 for the wrist flexors and with -4 for the wrist extensors. The duration of FES application was increased from 15 min at the very beginning to 1 hour at the end of the program. Once a week muscle torque measurement was performed with special measuring brace /4/. The joint torque was measured before the test stimulation, during the stimulation by applying train of rectangular pulses of constant parameters (pulse width 0.3 ms, frequency 20 Hz, voltage adjusted to different values for each muscle group) and five minutes after the stimulation.

Three effects of the program were investigated:
a) strengthening of the muscle groups
b) short term carry-over effects
c) long term carry-over effects.
Fig .5 presents the instrumentation for these measurements: measuring brace, laboratory voltage output stimulator (left), torque meter (right). The gauze-covered metal electrodes were daily mounted on the marked places of the upper extremity and were taken-off after each measurement.

V. Electrodes

Muscle contraction as a response on electrical stimulation depends much on placing and fixing the surface electrodes. It is not possible to obtain repeatable responses if stimulating points are changed from day to day. Therefore it is necessary to use adequate electrodes and an adequate mounting of them. The carbon-impregnated silicone rubber electrodes with gel are satisfying

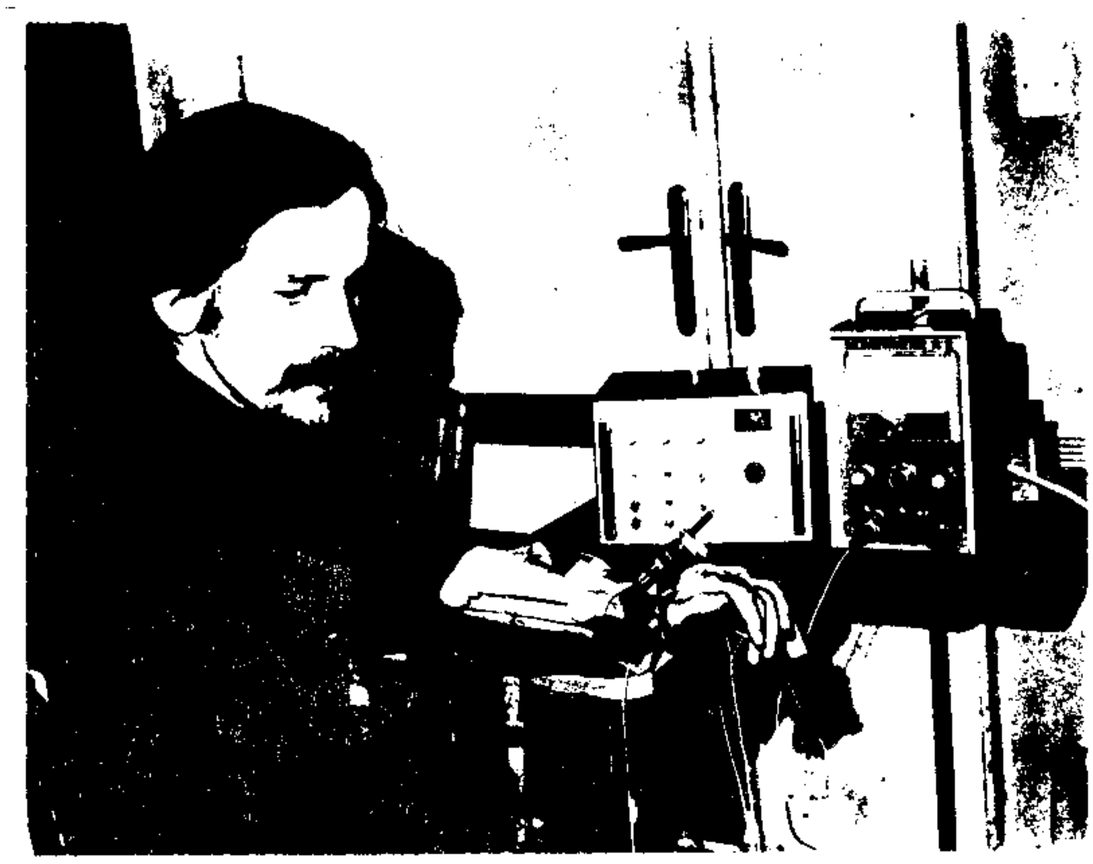

Fig. 5. Instrumentation for wrist movement measurements

the demands of prolonged FES program. Nelson et al. /6/ have reported on clinical effectiveness of them during electrical stimulation of quadriceps muscle in normal subjects. Similar tests were repeated with the same type but different dimensions of the electrodes in three quadriplegics (J.P. C6 lesion, B.P. C5-C6 lesion, M.G. C4-C5 lesion). Two types of adhesive tape were tested: syntheticacrylic polymer adhesive tape and T.E.N.S foam adhesive patch with microfoam brand surgical tape. They were tested for the endurance and the skin reaction. Patients were daily stimulated for half an hour. The wrist torque produced during the stimulation was measured and current through the electrodes detected. From the data of stimulating voltage and DC current relative changes in impedance were calculated. The amplitude of stimulating voltage during the test measurements was because of unpleasant sensations decreased from day to day. Two different sizes of electrodes were used for B.P. and M.G. (4.5 cm^2 and 17.5 cm^2) and electrodes with area of 17.5 cm^2 for patient J.P.

VI. Results

The described proportional control of the electrical stimulation with the stimulator placed under the armrest was well accepted by the patients because of relatively precise movements. They can grasp and release different small and heavy objects such as glass, safety razor, spoon etc.

The results of testing the FES orthosis on one patient with previously mentioned test are shown in Fig. 6. From the graph it can be noticed that the duration of the experiment was not reduced during the period of training.

Better results were obtained in strengthening program of wrist muscle groups. Although the voluntary control of the left

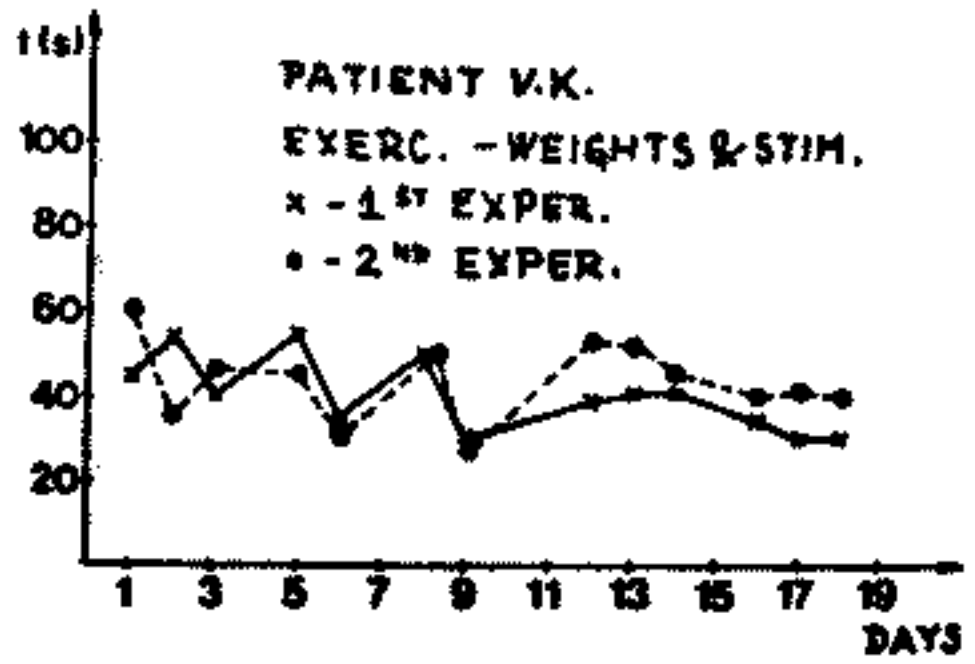

Fig. 6. Results of manipulation test

wrist of the patient V.K. was not improved and no carry-over effects were noticed, the electrically excited muscle force was increased. The results are given in Fig. 7 for wrist flexors (left) and for wrist extensors (right).

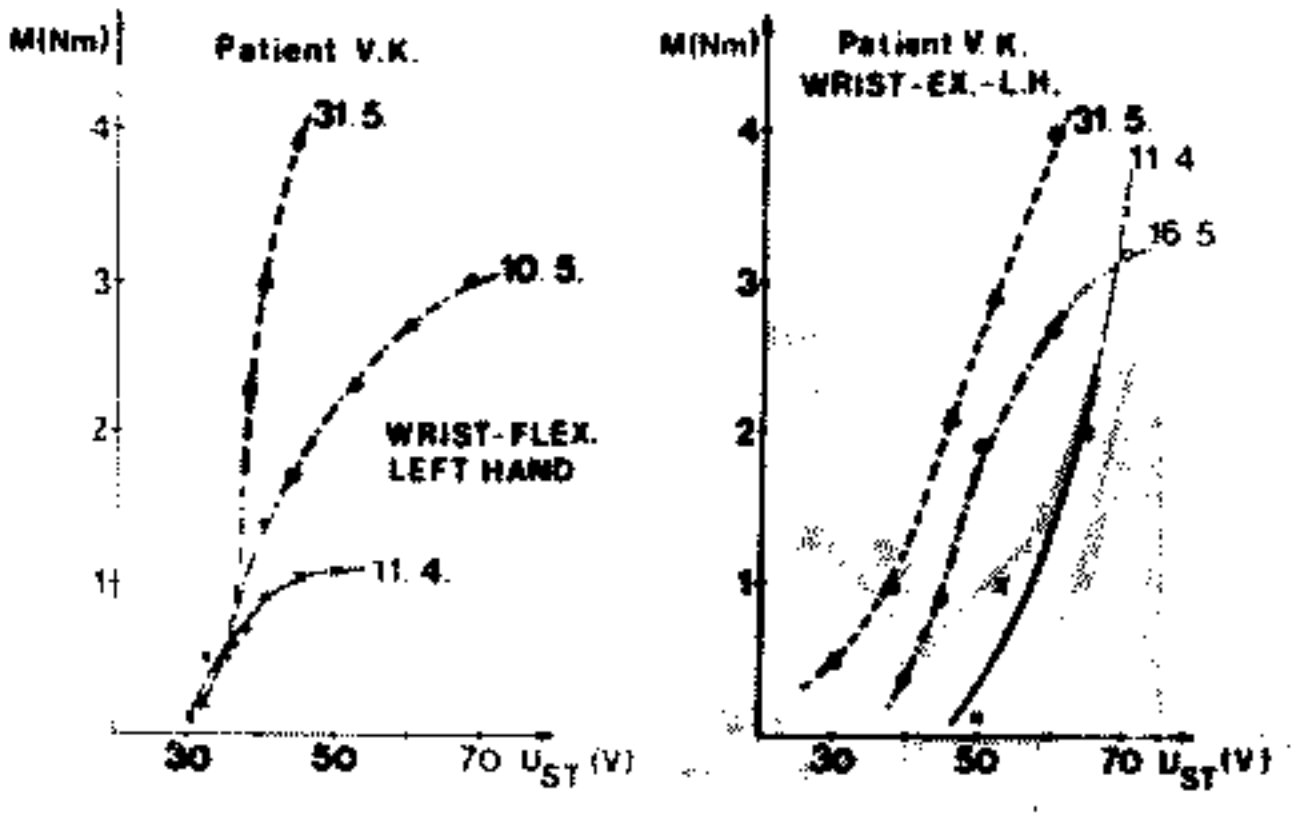

Fig. 7: Joint torque versus stimulation amplitude characteristics of paralyzed muscles

In the period of seven weeks three representative curves of muscle torque were recorded. Significant changes in maximal joint force can be seen in the flexors. For the extensor the curve is moving to the left during the FES program, that is, to the lower stimulation values for the same wrist torque. It is also evident that the voltage of threshold contraction has been noticeably reduced.

The results of electrode and adhesive tapes testing are as follows:

1) Carbon-impregnated silicon rubber electrodes are acceptable for prolonged FES of small muscle groups of lower arm.
2) Synthetic acrylic polymer adhesive tape of small sizes (70 cm^2 or less) is not usable for fixation of electrodes mentioned before. It is valid on relatively small muscle groups of wrist extensors and flexors. During daily activieies the tape gets off the skin and the gel is begining to dry. Among 12 electrodes only four remained in position for 4 days. Loosening of the adhesive tape was the reason for function failures of the electrodes.
3) T.E.N.S foam adhesive patches with area from 40 cm^2 to 72 cm^2 are excellent for adhesion of the same electrodes up to size of 17 cm^2. All of eight tested electrodes remained in position for the entire test period. Gel under the electrodes remained moist for five days and good contact between electrode and skin was enabled even under the smallest electrode with area of 4.5 cm^2 .
4) None of twenty electrodes resulted in skin reaction under the area of electrode contact. Only acrylic adhesive tape used to affix electrodes to the skin was source of little skin irritation in two patients. With the foam adhesive patches no changes on skin were observed at the end of the test period.
5) The average percent change in impedance between skin and electrodes during the four day test period is shown in Fig.8.

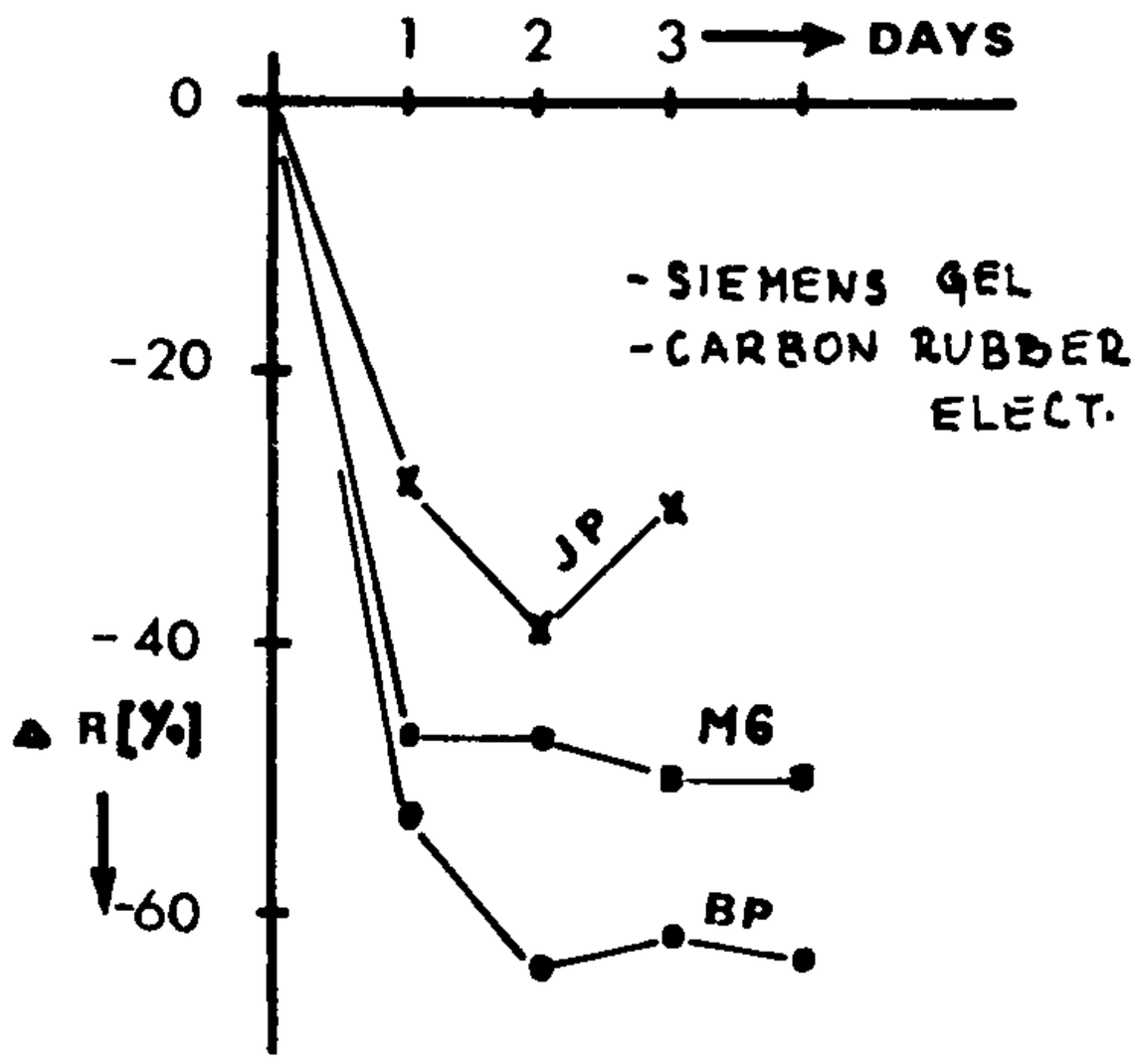

Fig.8. Relative changes of electrode - tissue impedance

The impedance was decreasing from 3,5 kΩ to approximately 1,5 kΩ when combination of one small (4.5 cm^2) and one larger (17,5 cm^2) electrode was used. It means that the change was at least 50 % of the initial value. These changes are the most noticeable during the first day. These findings are not similar to that of Nelson et al. /5/ who reported on positive changes for one gel used with the same electrodes or very little changes for another gel. It can be concluded that the type of the gel plays an important role in change of the electrode-tissue impedance.

6) Due to this fact an increase of muscle force produced by the wrist muscles was expected. This was proved by the results on two patients where at the end of the program the torque was twice as large as at the beginning.

VII. Conclusions

Not many researchers are working in the field of FES application in the restoration of the manipulation movements in quadriplegic patients. The reason is in difficulty of the problem which is so complex that it must be investigated separately for different spinal cord injured patients having different motoric deficiences. The researchers from Case Western Reserve University, Cleveland /7/, and the Polish group from Warsaw /8/ both are rising implantable electrode stimulation technique. The transcutaneous FES has in comparison with the implantable FES some advantages and disadvantages. It has been proved that it is possible to generate functional movements by surface electrical stimulation. For the prolonged stimulation carbon impregnated silicone rubber electrodes proved to be efficient when affixed with foam adhesive patches. This type of adhesive tape is far more acceptable than the synthetic acrylic polymer adhesive tape when compared to endurance and skin reactivity. The chosen combination of the electrodes and adhesive tape seems to be functional, convenient for application and cosmetic.

This electrical stimulator with proportional control of the paralyzed hand described above was well accepted by the patients. Although they are in use for a long period the stimulators are not yet systematically evaluated. The process of learning when controlling them have to be investigated as well. New control possibilities may bring further improvements in FES application to quadriplegic patients.

Acknowledgements

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