THE TIME-DEPENDENT OUTPUT OF PARAPLEGICS' QUADRICEPS MUSCLES ACTIVATED BY FES

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ABSTRACT

In this study, fatigue of the quadriceps muscles of paraplegic patients under functional electrical stimulation (FES) is analyzed myoelectrically and biomechanically. Electromyographic (EMG) parameters including latency, F-wave latency, conduction velocity and paired stimuli interval values showed no significant differences before, compared to after stimulation. The results got, show that fatigue of paralysed muscles under FES is not related to phenomena occurring in the nerve or neuromuscular junction, suggesting that they do occur in the muscle fiber itself. The quadriceps muscle force was continuously evaluate, during fatigue. This force was correlated with the peak-to-peak surface EMG amplitude, the latter measured directly from the M-wave of the stimulated muscle got during FES contraction. The possibilities to make use of surface EMG as an indicator of the force within the stimulated muscle to monitor fatigue are discussed.

KEY WORDS: FES, force, quadriceps, fatigue, EMG

INTRODUCTION

A major expression of fatigue of paralysed muscles activated by Functional Electrical Stimulation (FES) is the gradual decay of the force produced by the muscle, observed during stimulation, for a given set of stimulus parameters. The nature of fatigue of paralysed muscles under FES is essentially peripheral. Of the two aspects which characterize normal muscle fatigue, the peripheral and the central (2), the latter is absent in the muscles of the lower limbs of paraplegic patients. Besides this important feature, the precise nature of fatigue in paralysed muscles is still unknown.

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- ***Possible contribution of spinal reflex via gamma-loop activation of working muscles.***
- ***Role of 'parasitic' stimulation of the antagonist muscles, activated either directly, or via the reflex loop.***
- ***Possible existence of contralateral undesired activation.***
- ***Neural and neuromuscular junction condition.***
- ***Fatigue of the muscle fiber itself due to electrolytic and metabolic factors.***

The reduction of muscle fatigue has been associated with optimization of the stimulus parameters. For instance, it is generally agreed that lowering the stimulation frequencies decreases fatigue of the activated muscles (5,8,23,32).

When electrically stimulated, the paralysed muscles of the lower limbs of spastic paraplegic patients are isolated from voluntary control. If the only non-zero muscle forces are those of the actually activated muscles, the system mechanically analyzed can become determinate, allowing the transformation from joint torque to the forces acting in the individual muscles. This has indeed been done by this group for the continuous and non-invasive calculation of the quadriceps muscle force, from externally measured data (14,21).

Several attempts have been made to correlate muscle force and electromyographic activity (EMG) of different muscles of normal subjects (9,19,31,39). Furthermoree, methods of analysis of the EMG signal were developed to identify existence of fatigue from the signals obtained from this same population group (3,6,18,22). In electrically stimulated paralysed muscle, when activation is made synchronously, a repetitive myoelectric signal is produced. This signal may be obtained with suitable EMG equipment (30). The reason for this feature is that all, or almost all, the muscle fibers become activated simultaneously and a summation of the individual action potentials results in a compound muscle action potential (CMAP).

The myoelectric activity of stimulated muscles is a potentially important factor in expressing the time-dependent response of the muscle to its activation and its correlation to the resulting force developed. In this work, the mechanical and myoelectric outputs of the activated paralysed muscle during the fatigue are correlated together.

Fatigue in the contraction phase is studied. The other aspect of fatigue which is found in the recovery phase was not treated in this study due to the difficulties to identify the disturbances introduced by stimulation during the recovery process. An attempt was also made to identify the ranges of activation in which the surface EMG output can be used to predict the force existing within the muscle.

MATERIALS AND METHODS

The right quadriceps muscle of three spastic paraplegic patients, who were engaged in a FES training program and described in Table 1, were taken for our measurements. Of the different possible muscles, the quadriceps were selected due to the major role they have in weight bearing on the feet during standing (20) and walking (16), and due to the easy accessibility for force and surface EMG measurements.

	Years from Injury	Level of Injury	Age (Years)
NA	5	D8-9, L1	35
RI	2	D5-6	41
MJ	6	D5-6	42

TABLE 1 Description of patients taking part in this study

The muscles studied were considered trained, both relating to strength and fatigue resistance (5,24). External stimulation was applied with an adjustable electrical stimulator, providing monophasic rectangular pulse trains, with parameters of fixed values selected as follows:

- frequency 20Hz, pulse width of 0.2 msec and intensity up to 220 mA (corresponding to 110 V approximately) in accordance with previous results on optimization of stimulus parameters (32).

From the completely resting condition (first exercise of the test day), the quadriceps muscles were stimulated, and the various measurements were made. The initial stimulation values in every set of measurements were kept constant. The intensity used was sufficient for the creation of an electric field, by which all the quadriceps fibers were expected to be excited producing the maximal possible force. Such intensities correspond required for standing of the tested patient. This initial condition was followed by a gradual decay in muscle force due to fatigue.

a) Mechanical Measurements

A set of experiments was performed for isometric quadriceps force measurements. The patient was tested in the sitting position on an adjustable testing chair. The patient's thigh was attached to the seat, thus ensuring that the hip angle remained const ant during the tests. The measuring apparatus consisted of a pendulum, smoothly hinged at the level of the knee joint. The lower leg was attached, by hinging the foot at the level of the ankle joint, to the pendulum arm. The latter could be locked at any predetermined angle for isometric activation. Torque was measured by an instrumented horizontal cantilever, at the lower part of the pendulum arm. Force measurements versus time were made at 0, 30, 60 and 90 degrees of knee flexion angle and were on-line digitized at a sampling rate of 20 samples/sec into an IBM-XT computer.

b) Myoelectric Measurements

The measurement of myoelectric parameters related to FES can provide significant information. The rationale was to verify the possible effect of FES on the different components potentially involved in the activation.

Surface EMG was recorded using a MEDELC MS-92a apparatus. The following myoelectric measurements were made using standard electromyographic techniques (12) before FES and immediately after FES training:

1. Latency of the M-wave due to stimulations of the femoral, tibial and peroneal nerves was measured. Additionally, conduction velocity was determined for the peroneal and tibial nerves. F-wave latency was also measured on the peroneal and tibial nerves. These measurements were taken directly from the EMG apparatus. If the M-wave latencies or the conduction velocities were seen to be increased as a consequence of FES exercise, this could indicate neural participation in the fatigue process. On the other hand, a delay in the F-wave latency after FES training would suggest reflex participation in muscle activation.
2. The paired-stimuli technique was performed for evaluation of the recovery cycle of neuromuscular transmission in the patients' Femoral nerves. It is based on the acquisition of two action potentials from the quadriceps, of the same amplitude, at the minimum time inter stimuli. This test reflects the refractory period of the nerve and muscle, as well as any failure at the

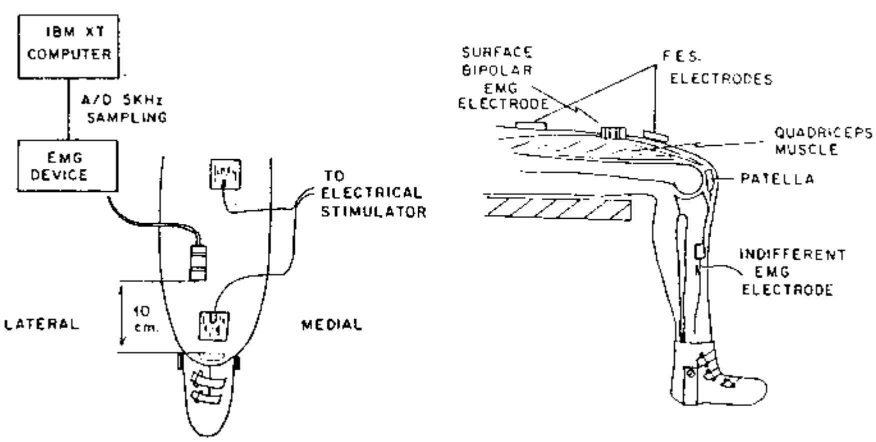

Figure 1. Arrangment of FES and EMG electrodes on the patient's thigh

neuromuscular junction. A time increase in the post-FES measurements could indicate the participation of such structures in the fatigue process.

3. Examination of crosstalk was made to verify whether the antagonists and contralateral muscles were active during stimulation of the quadriceps. Such activity could appear either at the same delay time from the stimulus artifact or, in the case of reflex activation, after a longer delay.
4. Recording of the M-wave of the quadriceps muscle during actual FES. In this test, surface EMG measurements were performed simultaneously with force measurements of the muscle during time. The arrangement of the FES and EMG electrodes is illustrated in Figure 1. The EMG signal was recorded on paper and in the same time was on-line digitized at 5000 sample/s, in to an IBM-XT computer during a 3 minute period. The M-wave

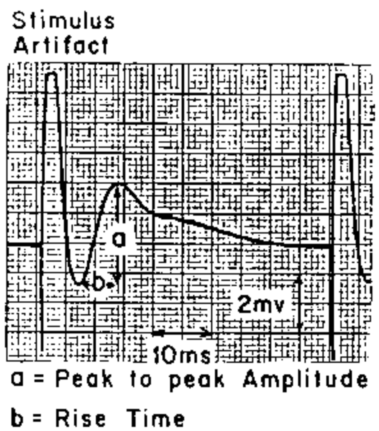

Figure 2. Definition of EMG parameters from a typical patient's recording. A repetitive characteristic M-wave was obtained after every stimulus artifact.

was found to have a repetitive waveform shape, shown in Figure 2. The stimulus artifact, found to last up to 5 msec, was followed by the CMAP; the same artifact signal could be seen in EMG traces from the beginning or from the end of the exercise (Fig.3), as well as from different patients. The defined parameters were the peak-to-peak amplitude (a) and rise time (b)(peak-to-peak duration), shown in Figure 2. Similar parameters were described in signal averaging of muscles of normal human subjects, without (18,19) or with electrical stimulation (9). These myoelectric parameters (a,b) and the absolute area under the curve (rectified integrated EMG signal) were extracted from the M wave obtained during stimulation by measurement from the digitized data. Statistical analysis of all the sampled data was also performed.

Each of the above tests was performed at least 3 times on every subject, from which averages were calculated.

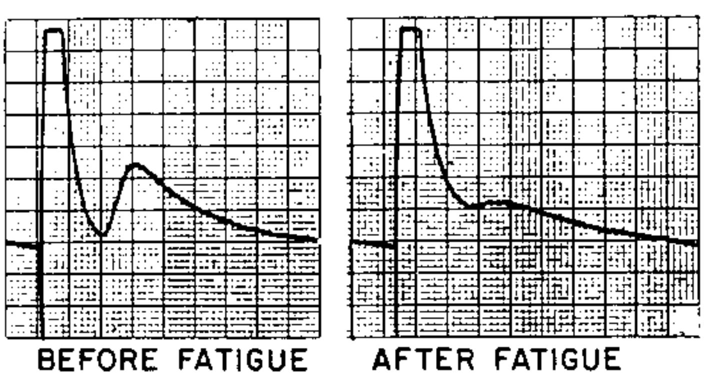

Figure 3. Stimulus artifact in an EMG trace corresponding to the beginning and the end of the exercise

c) Force evaluation

A biomechanical analysis of the lower leg forces was used to enable calculation of the time dependent force, generated in the stimulated quadriceps muscle (Fig. 4). The following assumptions were made:

1. During quadriceps stimulation, all non-stimulated muscles remain passive. This is justified since the four muscles which form the quadriceps group are the major muscles of the anterior thigh section, and are in close contact with the femur. They share the extension function, which is hereby analyzed, and are antagonized by the hamstrings group, located below the bone. In addition, by surface EMG measurements, no signal could be obtained from the antagonists during quadriceps stimulation. Following this assumption, the system can be considered statically determinate.

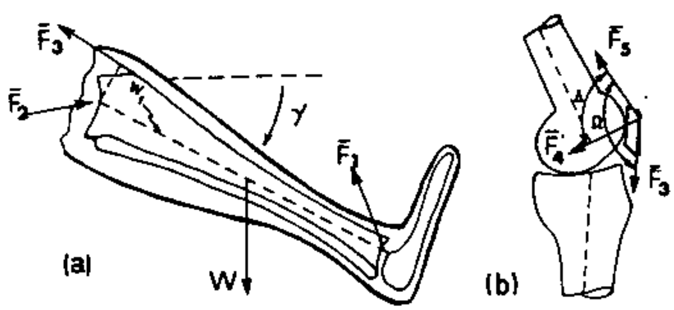

Fig. 4. Free body diagrams of the system treated: (a) shank, and (b) the knee joint.

2. Motion of the leg is considered two dimensional in the sagittal plane (with knee flexion-extension).
3. Forces in the tendons are assumed to act along their longitudinal directions.
4. At the knee joint, the tibio-femoral contact area is represented by a point in the sagittal plane. Data were taken from the literature for the Patellar lever arm (23) and the tendon displacement in relation to the knee flexion angle (1,34). These data,already considered the rolling and gliding motions of the knee. The analysis related towards both measured (the time dependent F1) and anatomical (w1,W,lever arms) data (Fig.4), the latter obtained either directly, or from data in the literature.

Equilibrium of static moments about the contact point K (Fig.4) enables to determine the patellar tendon force F3 and tibio-femoral joint force F2. Further, by using data published for the patello-femoral joint force F4 are calculated.

RESULTS

Mechanical

Typical decay curves of the isometric force in the quadriceps muscle during the fatigue are shown in Fig. 5. In all isometric positions shown, corresponding to 0, 30, 60 and 90 degrees of knee flexion angle, the force decay was continuous with a steep course, which levelled off at low force values after 100 sec approximately. Similar curves were obtained for the same subject in different days with identical measuring conditions.

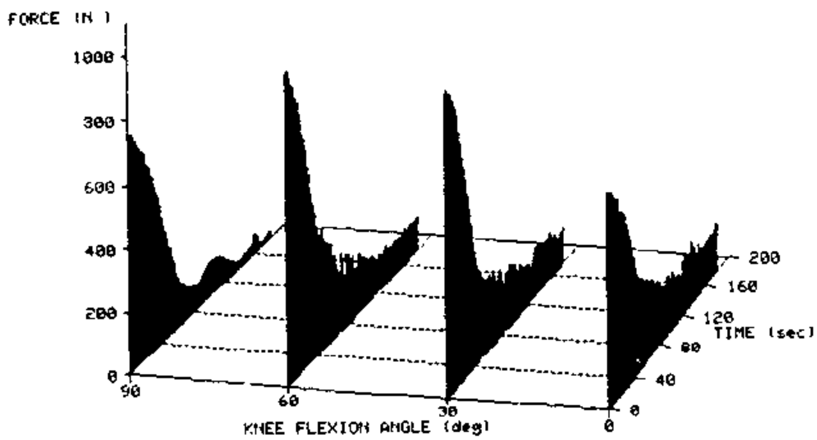

Fig. 5. Typical decay curves of the isometric force in the course of fatigue, corresponding to 0, 30, 60 and 90 degrees of knee flexion angle.

	Pre-FES	Post-FES
Latencies (ms):		
Femoral, distal	5.05 (0.66)	5.05 (0.59)
Peroneal, distal	4.30 (0.77)	4.22 (0.68)
Peroneal, proximal	11.76 (2.10)	10.63 (1.25)
Tibial, distal	4.57	4.33 (0.49)
Tibial, proximal	12.27 (1.34)	12.24 (1.96)
Conduction Velocity (m/s):		
Peroneal Nerve	51.44 (9.56)	56.03 (6.52)
Tibial Nerve	46.90 (16.88)	53.17 (12.85)
F-wave Latency (ms):		
Peroneal Nerve	48.58 (7.88)	47.67 (7.48)
Tibial Nerve	48.12 (2.40)	48.11 (6.55)
Inter-Stimuli Latency (ms):		
Femoral Nerve	21.83 (5.95)	14.63 (3.35)

Table 2. Summary of EMG test obtained in all 3 Patients. Values presented are averages (±SD)

Myoelectric

Summary of the myoelectric data pre and post FES is presented in Table 2. The values presented are averages for all three patients taking part in this study. The results presented indicate that stimulation had no effect on the following parameters: latency, conduction velocity, F-wave latency and paired-stimuli intervals (pre and post FES) differences were insignificant ($P<0.05$). This suggests that as a result of FES-induced fatigue, the condition of the nerve and neuromuscular junction remains unaffected.

No evidence of crosstalk between the stimulated quadriceps muscle, and its contralateral leg was found. At about the same delay time from the stimulus artifact, a very weak electromyographic response was recorded on the ipsilateral hamstring muscle, the antagonist of the stimulated quadriceps. This response was only noted at the highest levels of quadriceps stimulation, with no palpable muscular contraction in the hamstrings.

Force and myoelectric parameters in the course of fatigue were recorded simultaneously in 2 patients on their quadriceps muscles in isometric contractions at 30 degrees of knee flexion angle for 3 min. From the various parameters defined in Fig. 2, the peak-to-peak parameter was preferred as it gave a better correlation to force measurements. Typical curves of the peak-to- peak EMG amplitude against muscle force are shown in Fig. 6. Fitting was made by using a power curve $y = aX^b$, giving for all the cases studied, correlation coefficients r higher than 0.83. It is clearly seen that the peak-to-peak amplitude decreased during the course of fatigue, corresponding to the force developed within the muscle. At the same time, the time between the peaks and the absolute area under the EMG signal increased during fatigue, but with a lesser correspondence to force values. This behaviour was typical of the results obtained for both the patients in the various angles of isometric contraction. In some of the tests an early elevation of the peak-to-peak amplitude related to its initial value could be seen, giving normalized values over 1, and followed by an immediate decrease, all occurring during force decline. This phenomenon can be attributed to post-tetanic potentiation.

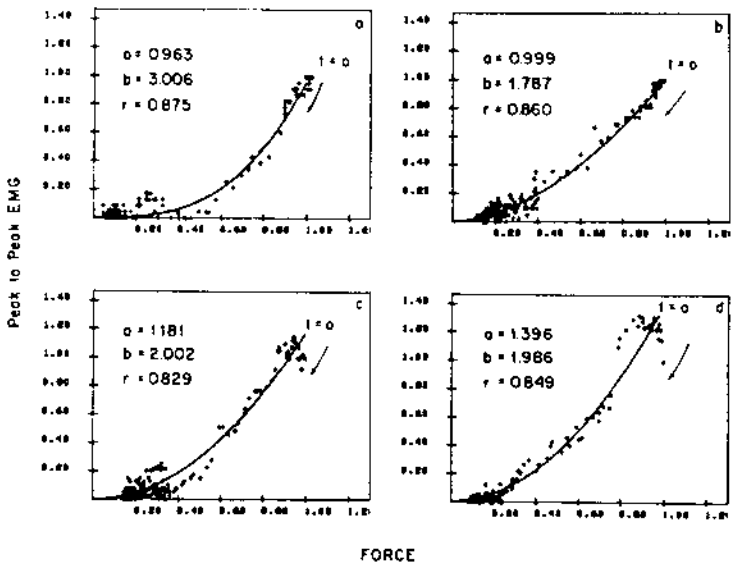

Fig. 6. Typical curves of the peak to peak EMG amplitude against muscle force. The solid line represents power curve fitting $y = aX^b$; (a) and (b): patient R I; (c) and (d); patient MJ. Note that $t = 0$ is at the right top of the curve an d that the arrow indicates time flow. The values in both axes normalized to their initial values.

DISCUSSION

A major question in FES is related to the mechanism of activation of the muscle, especially when using the surface stimulation technique, the merits of which are well acknowledged. One possible mechanism is through direct muscle stimulation and another one is activation of the motor nerve endings in the muscle (9) depending on the local electric field. Activation of the muscle by FES is accompanied by the appearance of the CMAP, which may easily be detected by surface EMG. The CMAP which is preceded by the stimulus artifact, takes the form of a repetitive signal (the M-wave). This type of signal was earlier observed by Stefancic et al (30) on the same type of patients and stimulation technique.

Our EMG results shed light on the questions related to the origin of fatigue of FES-activated paralysed muscles. In view of the absence of delayed secondary myoelectric signals, and the fact that no contralateral activation of the quadriceps or hamstrings muscles was noted, it may be deduced that no reactivation by reflex is achieved, neither in the agonist, not in the antagonist muscle groups. Muscle contraction thus results from the stimuli provided by the electrodes, which activate both the muscle fibers and motor nerve endings. It should be mentioned, though, that Stefancic et al (30) reported that when activating the quadriceps, sometimes weak reflex responses, with longer latencies in the triceps surae were detected.

A direct 'parasitic' activation of antagonist muscles was reached in our study only at the highest levels of stimulation, exciting minor electric muscle activity. Such weak activity appeared at the same time-delay from the stimulus artifact as the quadriceps CMAP. These findings are in agreement with the data reported by Stefancic et al (30).

The nerve conduction studies performed pre and post-fatigue induced by FES and including latency, F-wave latency and conduction velocity of the major nerves of the lower limb showed that these parameters were not affected significantly as a result of FES. Furthermore, the paired stimuli EMG technique allowed us to look into the condition of the neuromuscular transmission mechanism after fatiguing by FES. The results showed that there was no time increase between the similar double-signal appearances. Instead, a relative but non-significant time shortening was observed, which may be attributed to post-tetanic potentiation and immediate neuro-transmitter availability. These results thus indicate that the nerve and the neuromuscular junction are still in functional condition, even after induced fatigue by FES training. This somewhat contradicts what has been earlier suggested by Kralj et al (13) and Turk et al (33) related to the neuromuscular junction origin of fatigue. Hence, it appears that under tetanic stimulation, such as that produced in our study, the source of the muscle fatigue process lies in the muscle fiber itself, i.e. in metabolic, electrolytic and energetic factors.

The mechanical determinacy of the leg of a paraplegic patient in which the only muscle forces are those of the activated quadriceps, allows non-invasive determination of these forces. In this analysis, the knee geometry is of utmost importance. Recent reports of Van Eijden at al (34), in agreement with those of Ahmed et al (1), described the detailed parameters of the patellofemoral joint, including the positions of the tendons in relation to the knee flexion angle. These parameters were taken in to account for our force analysis, rejecting the older misconceptions of "pulley" knee mechanism. Some differences, though, were noted among the various recent reports, concerning the patellar tendon lever arm data (7,23,35), to which the biomechanical analysis is most sensitive and by means of which the joint torque is translated into muscle force. The data of Nisell (23) were preferred in the present study.

The time course of the quadriceps force obtained in this study indicated a gradual decrease. The force decay due to fatigue obtained is qualitatively similar to that reported for normal subjects or experimental animals. Due to the differences in the populations tested and in the methods of activation, the following should be pointed out:

1. Quadriceps isometric contraction under FES is always tetanic (for functional purposes). This is somewhat analogous to maximal voluntary contractions of normal muscles, lacking voluntary and subjective factors, associated with central fatigue (2,6).
2. Constancy of frequency of stimulation under FES governs the muscle fiber activation in complete lesion paraplegics. The involuntary spastic activation in these patients, as long as it is present, was reported to

decrease as a result of FES use (36), therefore no muscle input signal, other than that provided by FES, should be considered. The usual mechanism of motor unit recruitment and firing rate regulation present in normal muscle (6), are replaced here by a synchronic and massive fiber contraction.

3. It has been shown, by using imaging techniques (11,25,26), that muscle fibers undergo hypertrophy after extensive FES, as a result of which its cross-sectional area is increased. Moreover, it has been observed that long-term low frequency electrical stimulation induces a reversible fast-twitch to slow-twitch fiber transformation (27), in spite of the initial opposite trend due to spinal cord transection (15).

The gradual decay in the obtained force curves indicates loss of force-generating capacity, starting already in the very early stages of activation. In fatigue of non-paralysed muscles, some investigators have reported the same continuous process (4,37), but others have rather identified a clear failure point (6), possibly of myoelectric origin. Certainly, in our patients, tetanic contraction muscle blood flow restriction. Such mechanical compression may have resulted from enhanced intramuscular pressure which impairs blood flow in spite of the possible metabolically induced vasodilatation (28). The sympathetic vasoconstriction component may, in this case, be different from those of normal muscles, due to its complete spinal lesion involving part of such sympathetic fibers. Furthermore, the biochemical energetic supply would play a significant role both in the contraction and recovery phase, details of which would require further research. The force decay was finally completed after a period corresponding to 2-3 min of activation, reaching negligibly small force values.

Contradictory results are found in the literature, on the relationship between force and EMG in non-paralysed human muscles and in experimental animals. Milner -Brown and Stein (19) reported on a linear relationship between the mean rectified surface EMG and force of the first dorsal interosseous muscle (FDI). Vredenbergt and Rav (38) found an invariably non-linear relation between force and EMG activity of the biceps, in static conditions and at different muscle lengths. Woods and Bigland-Ritchie (39) suggested that during isometric voluntary contractions, the relationship between myoelectric activity and muscle force depends on the characteristics of the fibers of the muscle examined rather than on the methodology employed. Linear relations were obtained in muscles with predominantly uniform fiber composition, on which the frequency coding for force modulation depended. Non-linear relations were reported in muscles with a mixed fiber composition, some of which are recruited throughout its total force range. Solomonow et al (29) suggested for animal muscles a dependence between motor unit recruitment properties of individual muscles and EMG-force relationship. Linearity was obtained whenever the muscles required complete recruitment to generate 50% of the maximal force; a non-linear relationship was, however, indicated when increasing the recruitment range. Dealing with fatigue of sustained voluntary contractions, Stephans and Taylor (31) reported a linear relationship between the decay of EMG and force, in FDI muscle. Hultman and Sjoholm (9) reported that, in normal volunteers, electrically stimulated quadriceps depict a proportional decrease of EMG amplitude and force during fatigue, with different behaviour in recovery.

In stimulated muscles of paraplegics, our results indicated that the decreasing force was usually accompanied by a reduction in the peak-to-peak amplitude of the M-wave in a non-linear manner (excepting the sometimes seen initial elevation, probably due to post-tetanic potentiation). In this case, the quadriceps muscles involved are supposed to be non-uniform in their fiber composition, without having the possibility of force modulation by frequency variations. Total range of recruitment is thus requested for tetanic contraction, as has in fact been suggested by most of the previous authors.

Simultaneously, though to a lesser degree of consistency, the rise time of the M wave was observed to increase during force decrease, a fact which could be compared to a decrease in high frequency components, reported in normal muscles (6). In paralysed muscles, which are synchronically stimulated, the concept of motoneuron discharge rate or motor drive seems inapplicable, and the early peak- to-peak decline of EMG amplitude due to fatigue is probably derived from electrolytic changes in the muscle cell in the membrane of which the conduction velocity is slowed down. Juel (10) demonstrated that the action potential propagation velocity decreased by an increased extracellular potassium concentration and by a low intracellular pH. He associated the potassium increment outside the cell with broadening of the action potential resulting in an increased number of inexcitable cells. Those findings confirm the suggestions of Milner-Brown and Miller (18) about muscle membrane changes during fatigue, where they also concluded that the level of excitation of the membrane and impulse propagation velocity are reduced, depending on the duration and degree of fatigue, as well as on the intrinsic properties of the muscle studied. The decrease in force generating capacity during fatigue was also related to changes in high energy phosphates (17) and to failure of excitation-contraction coupling associated with impaired calcium release from the sarcoplasmic reticulum (4,37). Furthermore, the studies on the muscle recovery following activity showed a multiphase process (17) which could explain the loss of EMG-force relation in recovery reported by Hultman and Sjoholm (9). It is thus suggested that the fatigue observed in stimulated paralysed muscles is due to temporary changes occurring within the myofiber itself and that the EMG amplitude decline may not be solely related to the force throughout the entire process of decay of this latter parameter. Our results on EMG-force correlation could reveal, though, a correspondence between these two parameters in the first 60% portion of the fatiguing process, as expressed by the force. It is believed that this relationship obtained may be used practically in the future for non-invasively monitoring the force developed within the muscle and accordingly for controlling the stimulus parameters required.

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