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Predicted and Measured Muscle Forces after Recoveries of Differing Durations Following Fatigue in Functional Electrical Stimulation

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Abstract: Using ^{31}P nuclear magnetic resonance (NMR) spectroscopy, the bioenergetics of paralyzed muscles activated by functional electrical stimulation (FES) were studied in vivo during fatigue and recovery on paraplegic subjects. During the activation phase of the muscle, the muscle force was also monitored. The phosphorus metabolites were found to vary systematically during fatigue and to recover slowly to their rest state values after cessation of FES. During fatigue, a good correlation was found between the decaying force and each of the profiles of phosphocreatine, inorganic phosphorus, and intracellular pH. A musculotendon 5 element model was proposed for the activated muscle to predict its force generation capacity. A fatigue recovery function, based on the metabolic profiles, was introduced into the model. This model allowed us to predict the force expected to be developed as a function of the time after recovery of given time durations. Validation experimental measurements of force were carried out and included recurrent fatigue tests, both in the initially unfatigued state and at various times in the postfatigue stage of the muscle. Comparison of the predicted and measured forces indicated satisfactory agreement of the results. The developed model of muscle dynamics should help to design a strategy for reducing muscle fatigue under FES. **Key Words:** Bioenergetics of paralyzed muscles—Muscle fatigue.

Two major issues are associated with functional electrical stimulation (FES) of a muscle: the mechanism of force generation by the recruitment of the muscle fibers, and the decay of muscle force with time as a result of muscle fatigue (6,8). The musculoskeletal system of the human limbs is usually treated as dynamically indeterminate if the forces in the individual muscles are to be determined because of the larger number of unknowns as compared to the number of equations. In a paralyzed limb activated by electrical stimulation, the degree of mechanical indeterminacy can be reduced because the muscles of this limb are isolated from voluntary control and because the number of activated muscles and the level of excitation can be controlled (3). This is a unique situation because it allows the calculation of the actual muscle force from the externally measured torques and the correlation of this direct muscle output to parameters of other natures, such as metabolic or myoelectric parameters.

Metabolic parameters monitored by ^{31}P nuclear magnetic resonance (NMR) spectroscopy, including phosphocreatine (PCr), inorganic phosphorate (Pi), and intracellular pH, have been shown to indicate muscle force capacity in FES (2,3,5). The decaying force and pH level were found to correlate to each other, and this correlation (5) was used as a basis for the incorporation of a fatigue function into a musculotendon model of the activated muscle (3). In the present study, the relationships between muscle force in FES and metabolic parameters were studied to enable the development of a model of the activated limb, by which the force output can be predicted.

MATERIALS AND METHODS

The sets of measurements in this study were made on 5 paraplegic subjects. Transcutaneous electrical stimulation of the paralyzed muscles of paraple-

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gic subjects was of tetanic form, delivered by a microprocessor controlled current–output stimulator (7). The stimuli were rectangular with a duration of 0.25 ms and frequency of 20 Hz (10). The stimulation intensity was supramaximal and was obtained in each subject from the recruitment curves. Thus, it could be expected that all the muscle fibers would become activated at the onset of stimulation, producing, within a time period of seconds, maximum muscle activation. From this initial condition, a gradual decay of the muscle output would follow as a result of fatigue.

Mechanical measurements

With the thigh attached to the seat, the lower leg was attached, by hinging the foot at the level of the ankle joint, to a load cell. The torque about the knee joint was measured isometrically versus time at a 30 degree knee flexion angle. The torque was digitized on line at a sampling rate of 2,000 samples/s. To ensure unfatigued conditions of the muscle, each test was made at the beginning of the training day before any electrically induced activity took place. Each test included two contractions, one of 3 min and one of 100 s, separated by rest periods of differing durations: 3, 6, 9, 12, 15, and 30 min.

^{31}P NMR measurements

Levy et al. (5) have provided a detailed description of the metabolic measurements. These measurements included metabolic spectra and force measurements. The continuous stimulation, the force recording, and the ^{31}P NMR measurements were sampled simultaneously within the MR clinical 1.9 T instrument operating at 32.9 MHz for ^{31}P spectroscopy and at 81.3 MHz for ^{1}H imaging. A hydrogen/phosphorus double tuned surface coil served for both imaging and spectroscopy. The coil operated in a transmit/receive mode. Field shimming was performed on the ^{1}H signal.

MUSCLE MODEL

By solving the dynamic equations for the lower leg, it is possible to obtain the quadriceps tendon force, given the external loads and the anatomical and anthropometic data. The musculotendon model that was used for this study is shown in Fig. 1. The muscle's active element is represented by the muscle contractile element (CE). The passive elements in the muscle fiber are represented by the passive parallel-elastic component (PE) (4). The muscle viscosity caused by the presence of the fiber fluids is represented by the viscous element (VE) (1). The variable l_m represents the average muscle fiber

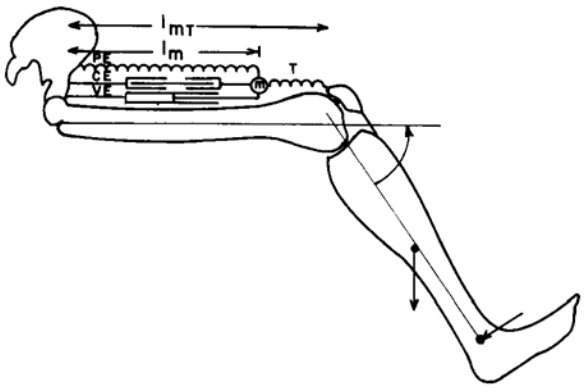

FIG. 1. The musculotendon model of the system is shown.

length. The tension present in the PE depends on the muscle length l_m. This tension, when combined with the tension produced by the CE, yields the total muscle force for a particular level of activation (9). The forces in the tendon (F_t), the PE (F_p), and the VE (F_d) elements were analytically represented by the following relations:

$$F_t = f_t(l_t) = f_t(l_{mt} - l_m) \quad (1)$$

$$F_p = f_p(l_m) \quad (2)$$

$$F_d = f_d(\dot{l}_m) \quad (3)$$

The variables l_t and l_{mt} indicate the tendon length and the length of the musculotendon, respectively. The force in the CE element was represented by the products of the following length–tension, velocity–tension, fatigue–recovery (normalized) and activation functions (a):

$$F_l = f_l(l_m) \quad (4)$$

$$F_v = f_v(\dot{l}_m) \quad (5)$$

$$F_{pH} = f_{pH}[pH(t)] \quad (6)$$

$$a = a(t) \quad (7)$$

The intracellular pH level was designated to represent fatigue within the active contractile element. The procedure included least square curve fitting of the pH decay with respect to time, t, during electrical stimulation and recovery, respectively.

$$pH^{F}(t) = c_1 - c_2 \tanh [c_3(t - c_4)]; \quad (8)$$

$$pH^{R}(t) = d_1 + d_2 \tanh [d_3(t - d_4)] \quad (9)$$

with constant parameters c_1, c_2, c_3, and c_4 for fatigue and d_1, d_2, d_3, and d_4 for recovery.

The balance equation yields the following musculotendon model:

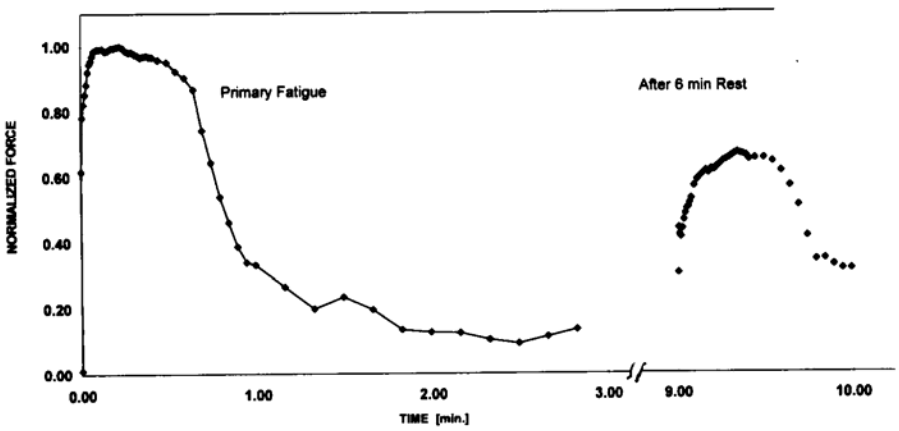

FIG. 2. Typical fatigue curves are plotted.

$$\ddot{l}_m(t) = \frac{1}{m(\cos\alpha)} f_t(l_t(t)) - \frac{1}{m}\left(f_p[l_m(t)] + f_d[l_m(t)] + f_l[l_m(t)] f_v[l_m(t)] f_{pH}[pH(a,t)]\, a(t)\right) \quad (10)$$

It should be noted that the musculotendon length l_{mt} is treated as a measurable constant because the experimental trials analyzed in this study were performed isometrically.

RESULTS AND DISCUSSION

Typical fatigue curves of force are shown in Fig. 2 in two conditions: initially unfatigued and after a rest period of 9 min. The metabolic results of 5–6 measurements performed on each of the tested patients are shown in Fig. 3. The tetanic stimulation induced very prominent changes in the steady-state levels of the phosphorous metabolites. There was a decrease in the intracellular pH to about 6.2, which was found to correlate to the decay in the quadriceps force during stimulation. The recovery process is also illustrated in Fig. 3. The pH values returned gradually to their steady-state levels after about 35–40 min of recovery. There was a similarity in the behavior of the quadriceps muscles of all the patients.

The model was run for two FES contractions, one of 3 min duration and one of 1 min duration separated by rest periods of 3, 6, 9, 12, 15 and 30 min. A predicted maximal force trajectory was obtained indicating a steady increase of the force with recovery time (Fig. 4). The results of parallel experiments, also indicated in the figure, show that there exists a good correspondence between the predicted and measured maximal forces.

The comprehensive approach, combining mechanical and metabolic parameters, has been presented to identify and resolve the major difficulties associated with artificial muscle activation. The pro-

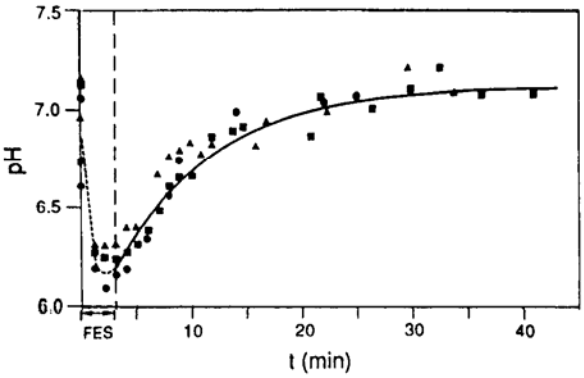

FIG. 3. The variations of intracellular pH in fatigue and recovery are shown on this graph.

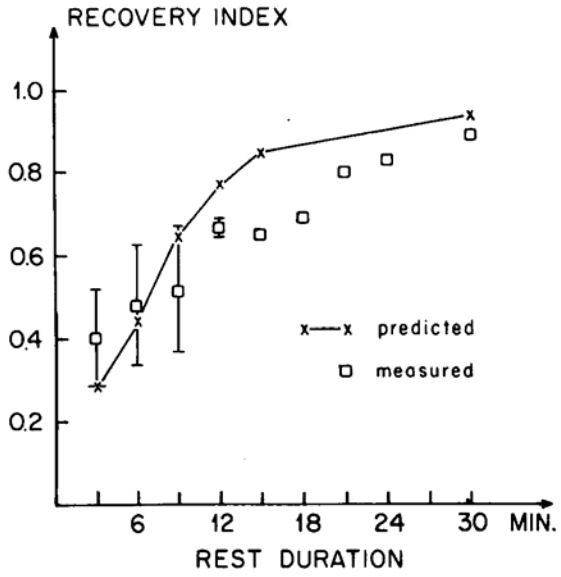

FIG. 4. This graph shows the correspondence between the model and measured maximal forces.

posed mechanical model provided the means to predict the force production capability of the muscle under different stimulation conditions. Learning the dynamic model of the muscle should enable the design of a strategy for reducing the muscle fatigue during FES. Additionally, the task of a feedback controller could be simplified because the feedback errors could be reduced and the stability of the system could be increased.

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REFERENCES

1. Bahler AS. Series elastic component of mammalian skeletal muscle. *J Physiol* 1967;213:1560–4.
2. Baker AJ, Carson PJ, Green AT, Miller RG. Influence of human muscle length on energy transduction studied by ^{31}P-NMR. *J Appl Physiol* 1992;73:160–5.
3. Giat Y, Mizrahi J, Levy M. A musculotendon model of the fatigue profiles of paralyzed quadriceps muscle under FES. *IEEE Trans Biomed Eng* 1993;40:664–74.
4. Huxley AF, Simmons RM. Proposed mechanism of force generation in striated muscle. *Nature* 1971;233:533–8.
5. Levy M, Kushnir T, Mizrahi J, Itschak Y. In vivo ^{31}P NMR studies of paraplegics' muscles activated by functional electrical stimulation. *Magnetic Res Med* 1993;29:53–8.
6. Levy M, Mizrahi J, Susak Z. Recruitment, force and fatigue characteristics of quadriceps muscles of paraplegics isometrically activated by surface functional electrical stimulation. *J Biomed Eng* 1990;12:150–6.
7. Minzly J, Mizrahi J, Isakov E, Susak E, Verbeke M. Computer-controlled portable stimulator for paraplegic patients. *J Biomed Eng* 1993;15:333–8.
8. Mizrahi J, Isakov E, Susak Z. Myoelectric and force characteristics in transcutaneous isometric FES. *Basic Appl Myol* 1994;4:147–54.
9. Stephenson DG, Williams DA. Effects of sarcomere length on the force–plate relation in fast- and slow-twitch skinned muscle fibers from the rat. *J Physiol* 1982;333:637–53.
10. Susak Z, Levy M, Mizrahi J, Isakov E. The duration of isometric contraction while using FES with stimuli of different parameters. *2nd Vienna International Workshop on FES,* Vienna, 1986;75–8.