〈Research Paper〉

Journal of the Korean Institute
of Industrial Engineers
Vol.6, No.1, June 1980

A Stochastic Model of Muscle Fatigue as a Monitor of Individual Muscle Capabilities

Myun W. Lee*

Abstract

This paper presents the validation of a stochastic model of muscle fatigue during static muscle contractions. Forty four laboratory experiments, covering eleven test conditions for two trained subjects, were run in order to estimate fatigue and recovery rates, based on EMG observations. The validation of the model was made by comparing the model predictions to the experimental fatigue time.

The validation study supports that the stochastic model of muscle fatigue accurately represents the underlying fatigue process. The study also provides support that the fatigue model can be used as a monitor of individual muscle capabilities.

Introduction

Assessment of isometric muscle strength has become increasingly important as it is realized that a large variation in the human attribute exists and is affected by many personal and environmental factors. As an example of a practical need for good strength assessment, some recent studies have shown that individuals with well developed strength capabilities are less prone to musculoskeletal strain and sprain injuries and back fatigue than their weaker counterparts when placed on manual materials handling jobs in industry(4, 27, 28). Also, there is a growing demand in rehabilitation medicine for a more objective means to assess a person's physical capabilities to return to a job requiring strength performance after suffering a musculoskeletal or deconditioning incident. For these as well as other general reasons it is necessary to improve on the existing methods available to determine a person's strength.

Functional attributes of skeletal muscle. It is well known that human skeletal muscle consists of motor units comprised of at least two distinct fiber types, i.e., fast twitch-high-glycolytic (Type F) fibers and slow-twitch-high oxidative(Type S) fibers(6, 11, 15, 16, 19, 29, 37). While (Type F) motor units tend to be more anaerobic, have higher muscle action potentials(MuAP) and faster contraction times(12, 29) Type S motor units tend to be more aerobic, less fatigable, slower contraction times and be recruited at lower tension levels(see Table 1). In the biceps it is estimated that there are roughly 200–400 motor units of which 40–60% are Type S motor units and the remaining being Type F motor units(9, 19, 32, 36).

---

* Seoul National University

Table 1. Selected Values of Durations, Amplitudes, and Frequencies of EMG Signals and the Estimated Conversion Factors for Type S and Type F motor units.

VARIABLE	TYPE S MOTOR UNITS	TYPE F MOTOR UNITS
Amplitude of MuAP(μV)	60	200
Duration of MuAP(msec.)	30	15
Frequency of Stimulation (Hz)	15	25
Conversion Factor	0.0135	0.0375

While muscle strength is the sum of twitch tensions from individual motor units, determined by the fiber type and frequency of stimulation, the EMG is the sum of MuAP's from the same motor units, again determined by the fiber type and frequency of stimulation. The relationship between the two has been suspected by many to be nonlinear(2, 30, 31, 38) probably because of the differential characteristics but orderly recruitment of motor units. At low tension levels where Type S motor units predominate the twitch tension and EMG amplitude increments for additionally recruited motor units are similar whereas at high tension levels where Type F motor units predominate the EMG amplitude increments are about 3 times greater than for Type S even though the twitch tension increments are similar(12).

In meeting the objective of the present study, the above mentioned observations were combined into an individualized stochastic muscle fatigue model(20) described in the earlier paper(21).

VALIDATION

The analytical muscle fatigue model can be evaluated by: 1) comparing muscle responses measured via EMG changes during a series of work/rest cycles with similar states of the muscle predicted by the model, 2) comparing experimental times to muscle fatigue with those predicted by the model. An experiment was designed to investigate the changes in the rectified surface EMG changes and to measure a subject's muscle characteristics from EMG changes and to measure a subject's cumulative work time until muscle fatigue.

Because of the applied interest in examining frequent, strenuous exertions, it was decided to use work intensities of 50%, 75% and 100% MVC, work periods shorter than the expected worker's endurance time at each intensity, and rest periods long enough to ensure immediate recovery from muscle fatigue. Thus at 50% MVC the work period was set at 5, 10 and 20 seconds, at 75% and 100% MVC 5 and 10 seconds. The frequency of exertion varied from 30 to 240 per hour(see Table 2).

Two male subjects were used(see Table 3). They were paid volunteers in good health, and had given written consents. Each was seated in a rigid chair with a lap belt and shoulder harness to limit upper trunk mobility, the use of extraneous muscle(see Figure 1). The elbow was positioned in an adjustable rest with the forearm at 90° to the upper arm with the forearm held in a supinated position so as to obtain maximum EMG signals from the biceps brachii.

After abrading the skin over the belly of the muscle and the lateral and medial epicondyle regions of the elbow with alcohol wipes, Beckman silver-silver-chloride electrodes were applied and allowed to set in until the DC resistance was below 50 kOhms. The belly of the muscle was used since that position presents cross-sections of more muscle fibers than other positions and consequently produces the largest EMG signal. The EMG signals were first amplified by a differential preamplifier with approximately infinite input impedance and were then conditioned by a Heath-Schlumberger AC Voltmeter which acted as a rectifier and smoother of the EMG signal. Both raw and rectified EMG signals were recorded on a Hewlett-Packard Instrumentation Recorder. The force of exertions was measured using a practically rigid strain gauge ring in a

Table 2. Test Series

INTENSITY OF EXERTION(%MVC)	WORK PERIOD(sec.)	REST PERIOD(sec.)	RATIO $\left(\frac{\text{REST PERIOD}}{\text{WORK PERIOD}}\right)$	NO. OF EXERTIONS PER HOUR
50	5	55	11	20
	5	25	5	120
	5	10	2	240
	10	30	3	90
	20	100	5	30
75	5	55	11	60
	5	25	5	120
	10	50	5	60
	10	110	11	30
100	5	55	11	60
	10	110	11	30

(All measurements were repeated once)

Table 3. Subject Characteristics

MEASUREMENT	SUBJECT	
	S1	S2
stature(cm)	182.3	189.0
weight(kg)	83.8	77.0
age (years)	21	20
upper arm length(cm)	31.	34.5
upper arm circumference flexed(cm)	32.9^{*}	29.5^{*}
	35.2^{++}	32.6^{+}
relaxed(cm)	30.6^{*}	28.8^{*}
	32.9^{+}	29.5^{+}
Maximum strength(kg)	33 *	27 *
(90° elbow)	38^{+}	31^{+}

* : measured before experiment

$^{+}$: measured after 3 months of experiment

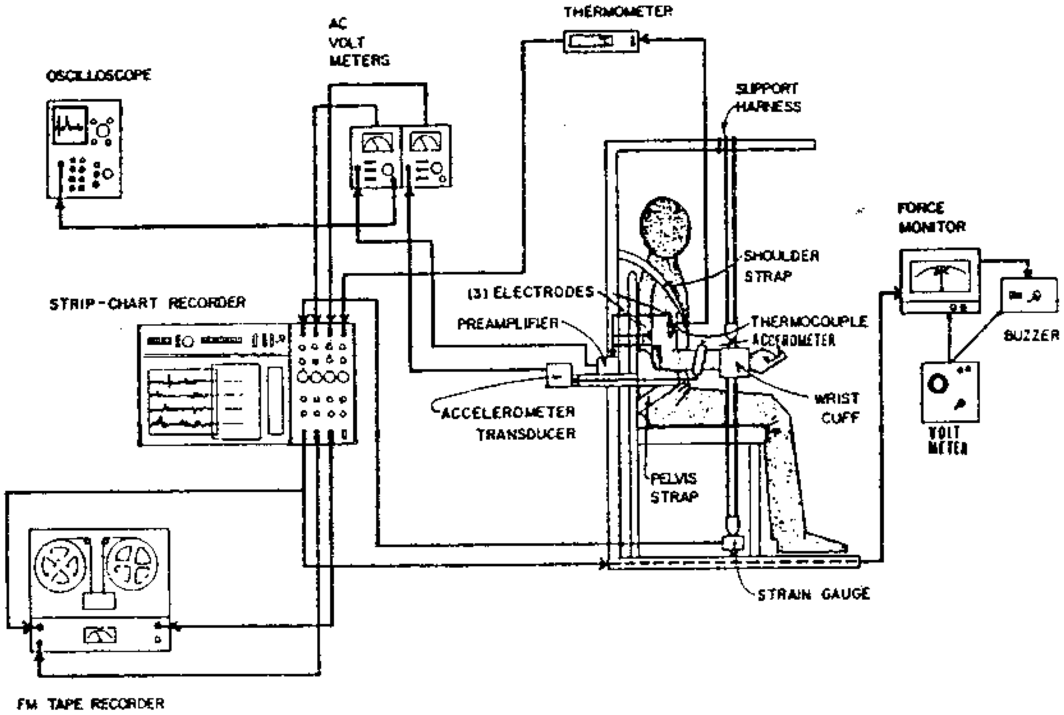

Figure 1. Schematic Drawing of the Experimental Set-up.

Wheatstone-bridge circuit configuration and was also recorded on the magnetic tape.

Test Procedure

After attachment and aging of electrodes, three maximum strength exertions separated by five minute rest periods were made. Based on these values, two force monitors were properly set by calculating %MVC and transforming the %MVC into voltage levels. At the onset of each work period, the subject was advised to reach the null point of the force monitor slowly at the verbal signal “get set”. As soon as the desired force was achieved, the experimenter instructed “start exertion” and an electric timer was activated. At the end of the work period, the electric timer signalled audibly for the release. At the same time a second timer for the rest period was activated.

The same procedure was repeated for each work/rest cycle until either the point of muscle fatigue was reached or four hours of experimentation had elapsed. At the termination of the sequence of work/rest cycles, a ten minute break period was given. After this the subject exerted three post exertion MVC’s and then a maximum strength, maximum endurance exertion until the force leveled off. This was designed under the assumption that the terminal plateau of force would be a good indicator of the proportion of the subject’s motor units left unfatigued. Furthermore, this exertion provided information on the change in the EMG amplitude between a resting state and a completely fatigued state of the muscle.

Analysis

The magnetic tape recordings were sampled through an A-to-D converter and stored. The signals sampled at 500 Hz during the work period were averaged at one-second intervals. Since the EMG increased linearly, the amplitudes were regressed as a linear function of time. The EMG intercept in Figure 2 represents the EMG amplitude at the onset of an exertion. The product of the slope of the i-th period times the length of the work period is defined as d_i. In Figure 2b each dot represents an average amplitude for a one-second interval and each line represents a regression line for each work period.

The variable EMG.REC, d_i and e_i were analyzed in detail using time series analysis. EMG.REC is the rectified EMG amplitude at the onset of an exertion, used as a measure of initial recruitment of motor units; d_i is the net increase in EMG amplitude during a work period, used as a

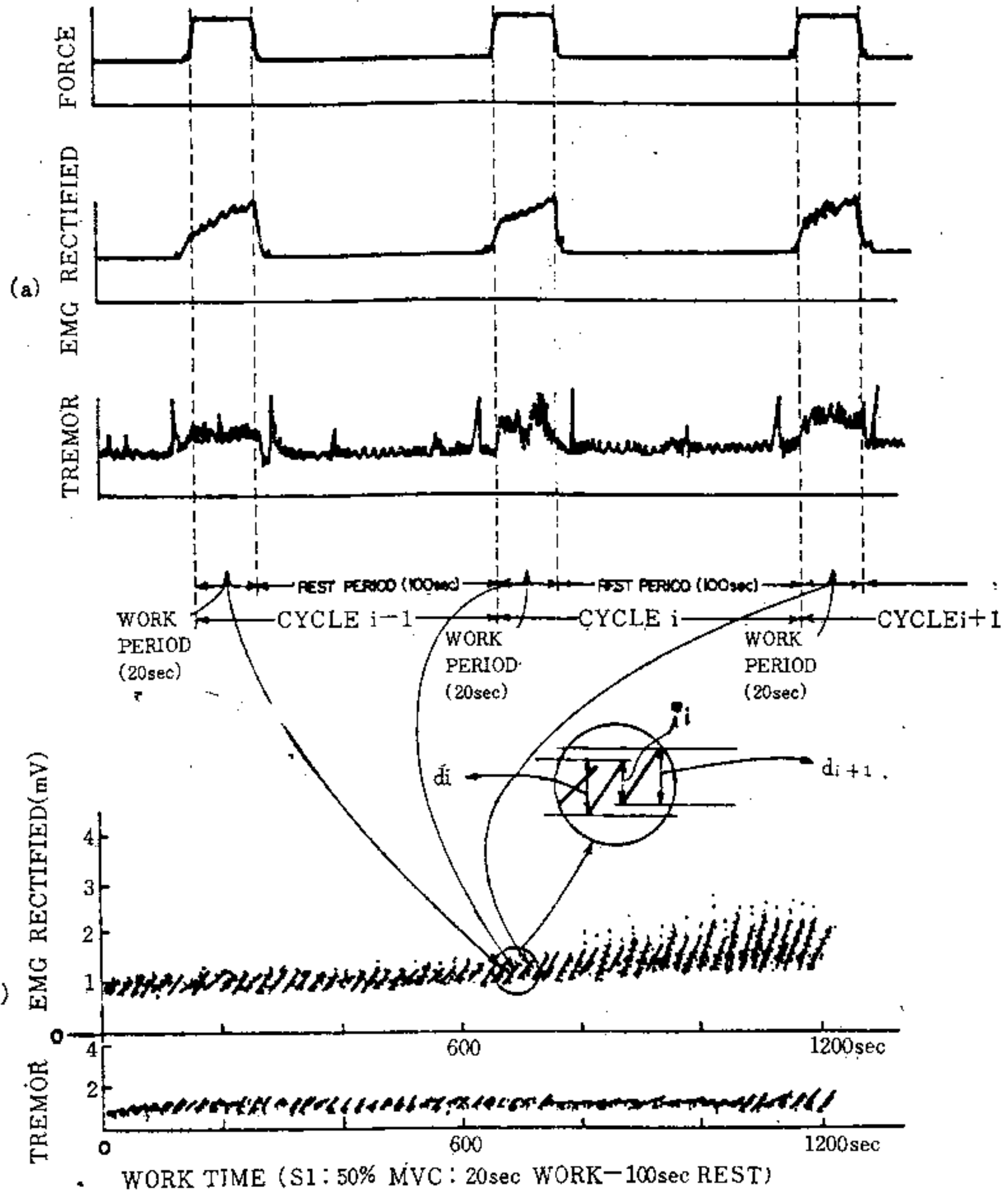

Figure 2. Example Output from (a) Strip Chart Recorder and (b) X-Y Plotter.

measure of additional motor units recruited in order to maintain a constant force and e_i is the intermediate recovery in the EMG amplitude during a rest period, used as a measure of recovery from fatigue.

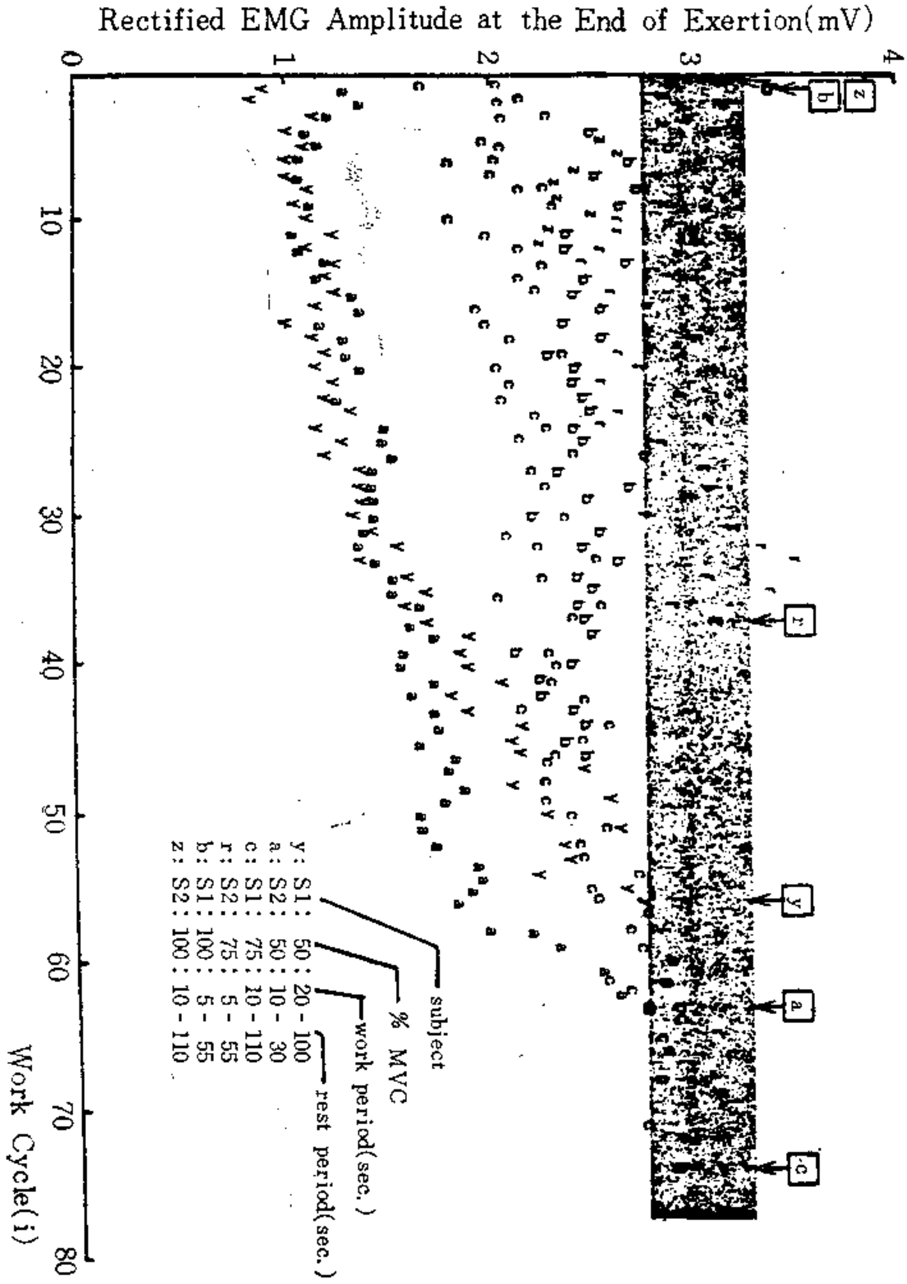

Figure 3. The Rectified EMG Amplitude at the End of Successive Work Cycles.

The average value of initial-EMG amplitudes showed a staircase increase with respect to increasing %MVC, which indicated that the initial amplitude is mainly a function of %MVC. The d_i's at 75% MVC are higher than the d_i's at 50%, while the d_i's at 100% MVC are lower than the d_i's at 75% MVC indicating that at 100% MVC there are fewer units left for additional recruitment. The final EMG amplitude at the point of muscle fatigue is approximately the same

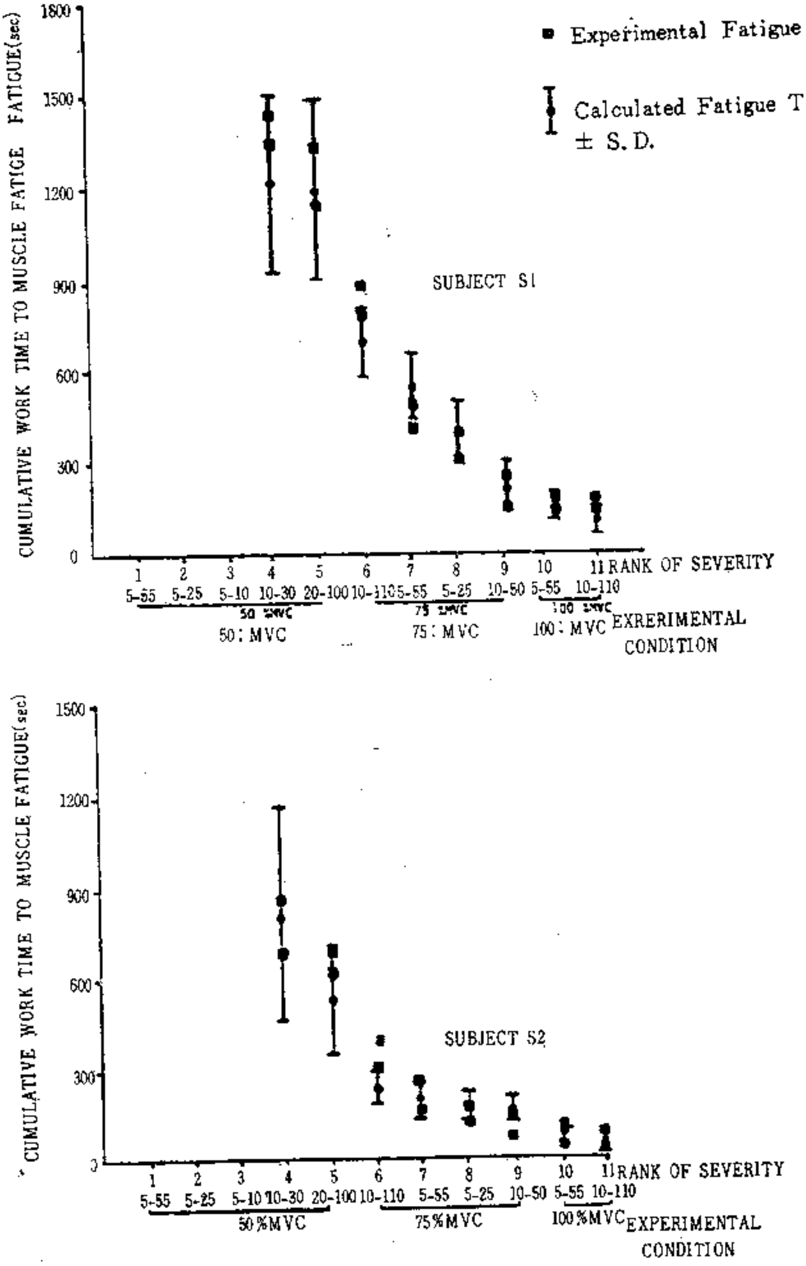

Figure 4. Experimental Fatigue Time vs. Calculated Fatigue Time by HMSD: Homogeneous Motor Units and State-Dependent Recovery Rate.

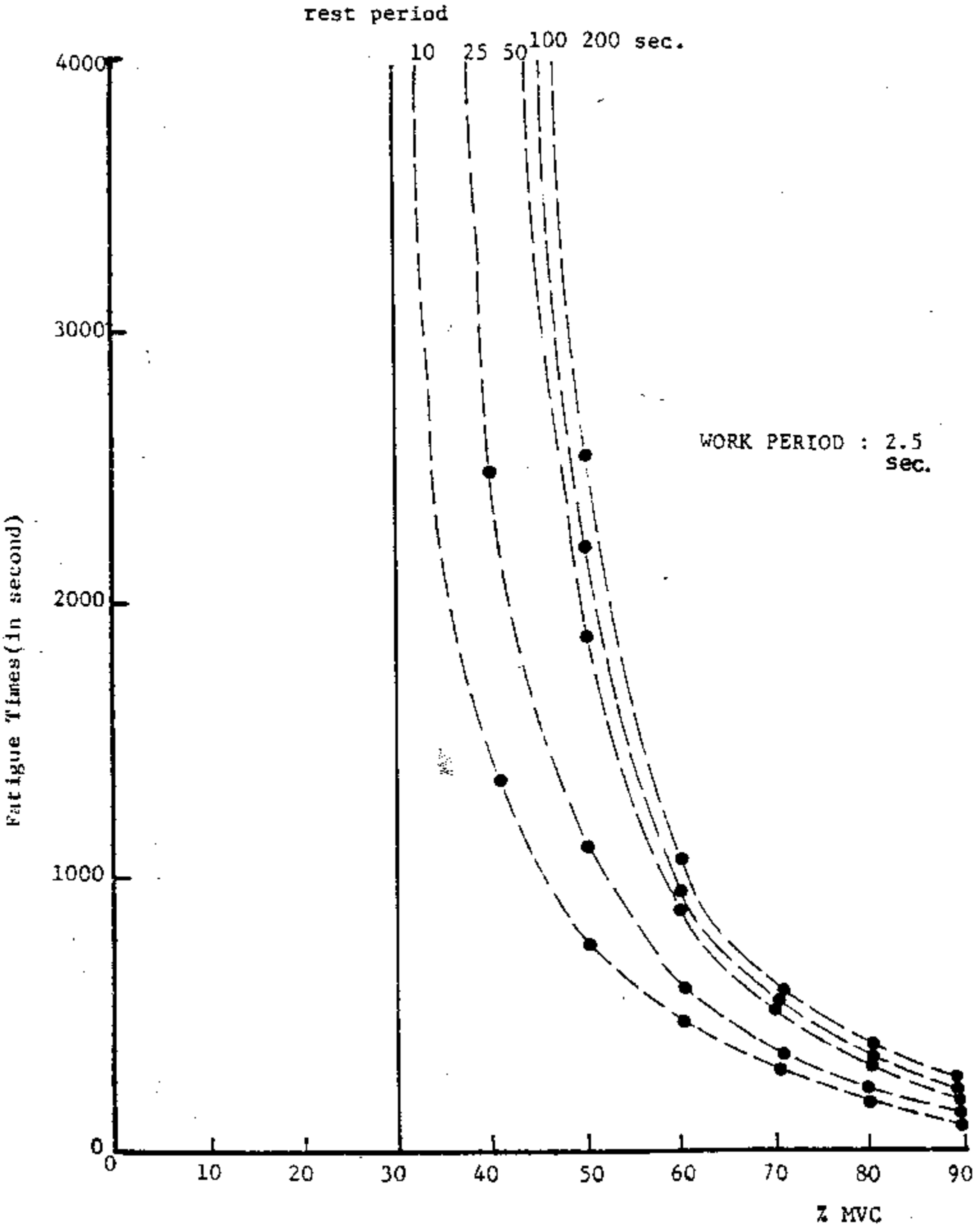

Figure 5. (a) Net Fatigue Time from 100% MVC to a Given %MVC: Work Period=2.5 seconds

(see Figure 3) providing a good linkage between EMG amplitude and muscle fatigue. The fundamental thesis states that the point of muscle fatigue will be reached when all active motor units are recruited, and when some of these recruited motor units become fatigued. If this is true, then the EMG amplitude at the point of muscle fatigue should reflect the total amplitude of all recruited motor units, i.e. a constant level.

Among several different models examined, muscle fatigue could be explained most accurately and simply using a simple stochastic process, a Markov Chain, with %MVC dependent fatigue rate and state-dependent recovery rate (the HMSD, see 21). A graph comparing experimental fatigue time and calculated fatigue time is shown in Figure 4. As can be seen the model underestimates for long periods and overstimates for short periods.

DISCUSSION

The experimental findings and model calculations do confirm that EMG amplitude is a consistent and senstitive measure of fatigue-recovery processes in short and frequent work-rest sequences. The subjective judgement of muscle discomfort was not found to be reliable measure. Therefore it is safe to assume that workers performing repetitive and heavy exertions do not sense the progress of fatigue accurately. Therefore several reference guide (Figure 5a and 5b) were calculated in order to facilitate the planning of rest periods into a worker's job schedule so as to avoid undue muscle fatigue. Figures 5a and 5b show the predicted fatigue times from 100% MVC to a given %MVC and also the maximum allowable strength requirement as a function of work period. The length of the work period seems to be the most critical factor which governs the MVC loss in frequent, strenuous static exertions. Also the decreasing efficiency of the recovery rate once exceeding 100 seconds can be observed as opposed to previous research on long work periods.

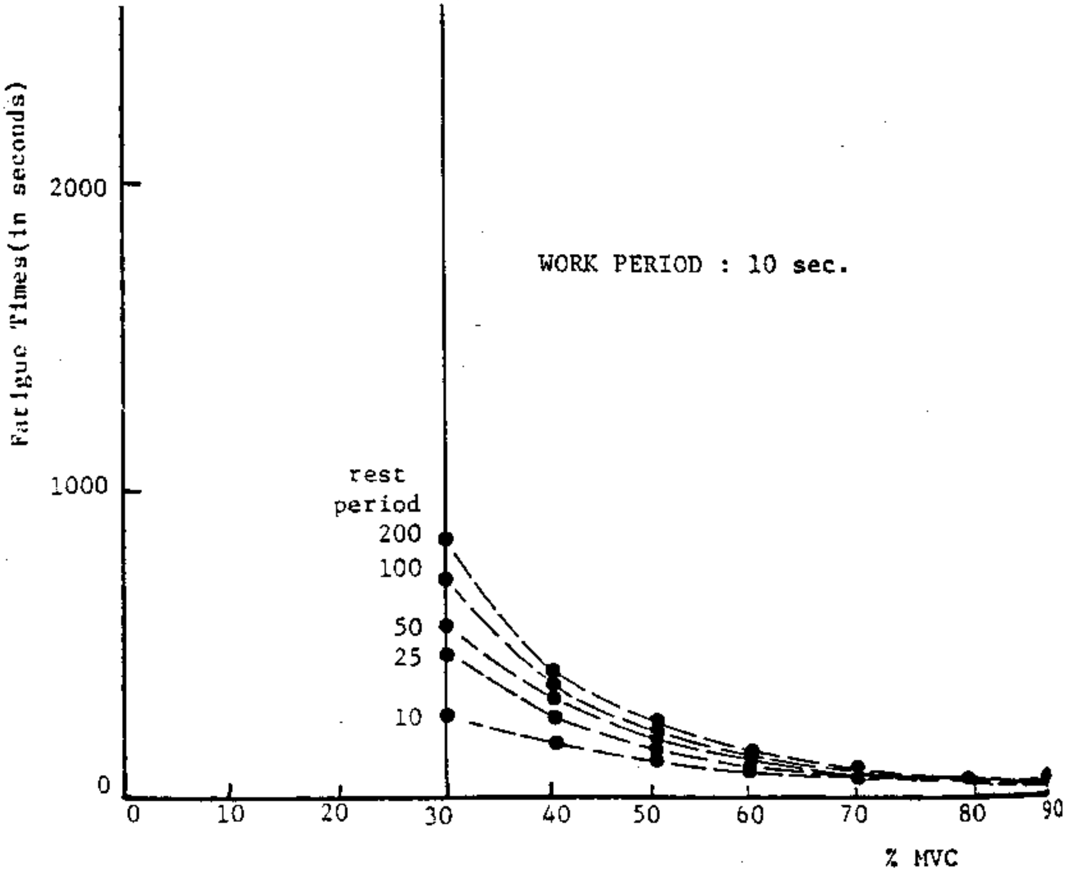

Figure 5. (b) Net Fatigue Time from 100% MVC to a Given %MVC: Work Period=10 seconds

Recommendations

Based on the results, the following recommendations can be made for industrial situations:

1) If the length of the work period is longer than 10 seconds, the job strength requirement should not exceed 40% MVC in order to avoid transient muscle fatigue.
2) A rest period longer than 25 seconds after 5 second exertion may be excessive at 50% and 75% MVC.
3) Even long periods of rest(55-100 seconds) may not be sufficient time for complete recovery after 5 seconds exertions at 100% MVC.
4) When conducting strength tests, the individual should be allowed a rest period of at least one minute between two successive short exertions(in the order 2.5 seconds) which insures an output of at least 95% MVC.
5) For a second of exertion longer than five seconds with an accompanying rest period shorter than 55 seconds, the individual's peak strength should be recorded instead of the mean measured strength since significant fatigue would occur during the exertion periods lowering the mean value obtained.

Acknowledgement

This research was partially supported by the Korea Science & Engineering Foundation. The author is indebted to Prof. Don B. Chaffin and Dr. Andris von Freivalds for their help, to Mr. Koo Hyung Lee for his assistance, to Miss Byung Sook Yoo for typing the manuscript.

REFERENCES

1. Bigland, B. and O.C.J. Lippold. "Motor unit activity in the voluntary contraction of human muscle." *J, Physiol.* 125:322-335, 1954.
2. Bouisset, S. "EMG and muscle force in normal motor activities." in *New Developments in Electromyography and Clinical Neurophysiology*, ed. J.E. Desmedt, 547-585. Karger:Basek, 1973.
3. Burke R.E., D.N. Levine, F.E. Zajac, and W.K. Engel. "Mammalian motor units: Physiological-histochemical correlation in three types in cat gastrocnemius." *Science*, 174:709-712, 1971.
4. Chaffin, D.B., G.D. Herrin, W.M. Keyserling and J.A. Foulke. "Pre-employment strength testing-an updated position." *J. Occ. Med.* 20(6):403-408, 1978.
5. Chaffin, D.B., M.W. Lee. and A. Freivalds. "Towards a More Objective Assessment of Muscle Strength From EMG Analysis." Med. Sci. in Sports. To be published in 1980.
6. Close, R.L. "Dynamic properties of mammalian skeletal muscles." *Physiol, Rheum.* 52:129-197, 1972.
7. Coggshall, J.C. and G.A. Bekey. "A stochastic skeletal mucle based on motor unit properties." *Math, Biosci.* 7:405-419, 1970.
8. deVries, H.A. "Efficiency of electrical activity as a physiological measure of the functional state of muscle tissue." *Am. J. Phys. Med.* 47:10-22, 1968.
9. Edstroem, L. and B. Nystroem. "Histochemical types and size of fibers in normal human muscles." *Acta Neurol. Scan.* 45:257-269, 1969.
10. Freivalds, A., M.W. Lee, and D.B. Chaffin, "Towards a Rest Allocation Scheme for Sequential Static Muscle Exertions." Human Factors Scociety Annual Meeting(Fall). Boston, Massachusetts, 1979.

11. Gollnick, P.D., J. Karlsson, K. Piehl, and B. Saltin. "Selective glycogen depletion in skeletal muscle fibers of man following sustained contractions." *J. Physiol.* 241:59-67, 1974.
12. Gydikov, A., N. Dimitrova, D. Kojarov and G. Dimitrov. "Influence of frequency and duration of firing on the shape of potentials from different types of motor units in human muscles" *Exp. Neur.*, 52:345-344, 1976.
13. Gydikov, A. and D. Kosarov. "The influence of various factors on the shape of the myopotentials in using monopolar electrodes." *Electromyogr. Clin. Neurophysiol.* 13:319-343, 1973.
14. Henneman, E. and C.B. Olson. "Relation between structure and function in the design of skeletal muscles." *J. Neurophysiol.* 28:581-598, 1965.
15. Hulten, B.A. Thorstensson, B. Sjoedin, and J. Karlsson. "Relationship between isometric endurance and fiber types in human leg muscles." *Acta. Physiol. Scand.* 93:135-138, 1975.
16. Johnson, J.P., D. Weightman and D. Appleton. "Data on fibre size in thirty-six human muscles." *J. Neurol. Sci.* 19:307-318, 1973.
17. Karlsson, J. "Lactate and phosphagen concentrations in working muscle of man." *Acta Physiol. Scand. Suppl.* 358, 1971.
18. Karlsson, J. and B. Ollander. "Muscle metabolites with exhaustive static exercise of different duration." *Acta Physiol. Scand.* 86:309-314, 1972.
19. Kosarov, D. and A. Gydikov. "Dependence of the discharge frequency of motor units in different human muscles upon the level of the isometric muscle tension." *Electromyogr. Clin. Neurophysiol.* 16:293-306, 1976.
20. Lee, M.W. *A Stochastic Model of Muscle Fatigue in Frequent Strenuous Work Cycles.* Ph.D. Dissertation, the University of Michigan, 1979.
21. Lee, M.W., Stephen M. Pollock and Don B. Chaffin "A Stochastic Model of Muscle Fatigue in Cyclic Heavy Exertions... Formulation" *J.KIIE*, 1979.
22. Lindström, L. "On the frequency spectrum of EMG signals." Technical Report, Chalmers University of Technology, Güteborg, Sweden, 1, 1970.
23. Milner-Brown, H.S., R.B. Stein and R. Yemm. "The orderly recruitment of human motor units during voluntary isometric contractions." *J. Physiol.* 230:359-370, 1973.
24. Milner-Brown, H.S. and R.B. Stein. "The relation between the surface electromyogram and muscular force." *J. Physiol.* 246:549-569, 1975.
25. Moeller, E. "The churning apparatus; an electromyographic study of the muscles of mastication and its correlation to facial morphology." *Acta Physiol. Scand.* 69:280, 1966.
26. Norris, F.H., Jr., and E.L. Gasteiger. "Action potentials of single motor units in normal muscle." *J. Electroenceph. Clin. Neurophys.* 7:115-126, 1955.
27. Paulson, E. and K. Jorgenson. "Back muscle strength, lifting and stooped working postures." *Applied Ergon.* 2:133, 1971.
28. Rowe, L.M. "Low back disabilities in industry; updated position." *J. Occup. Med.* 13:476, October 1971.
29. Sjodin, B. "Lactate dehydrogenase in human skeletal muscle." *Acta Physiol. Scand. Suppl.* 436, 1976.
30. Sica, R.E.P. and A.J. McComas. "Fast and slow twitch units in a human muscle." *J. Neurol. Neurosurg. Psychiat.* 34:113, 1971.
31. Simons, D.G. and E.H. Zuniga. "Effect of wrist rotations on the XY plot of averaged biceps EMG and isometric tension." *Am. J. Physiol.*
32. Sissons, H.A. "Anatomy of the motor unit," *Disorders of Voluntary Muscle.* ed. J.N. Walton, 3rd ed. Churchill Livingston, London, 1974.
33. Stephens, J.A. and A. Taylor. "Fatigue of voluntary muscle cantraction in man." *J. Physiol.* 220:1-18, 1972.
34. Stephens, J.A. and T.P. Usherwood. "The fatigability of human motor units." *Proc. of the Physiol.*

Soc., 37, 1975.

35. Stuart, D.G. and J.A. Stephens. "The recruitment order of motor units and its significance for the behavior of tendon organs during normal muscle activity." *The Motor System: Neurophysiology and Miracle Mechanisms.* Shahani, M. (ed.) Elsvier Science Publishing Co., New York, 1974.
36. Sulemana, C.A. and R. Suchenwirth. "Topishche unterschiede in der enzymhistologischen zusammensetzung der Skelettmuskulatur, Untersuchungen an 5 Skelettmuskeln von Verstorbene ohne Neuromuskulare Erkrankungen." *J. Neurol. Sci.* 16:433-444, 1972.
37. Thorstensson, A. "Muscle strength, fiber types and enzyme activities in man." *Acta Physiol. Scand. Suppl.* p. 433, 1976.
38. Zuniga, E.N. and D.G. Simons. "Nonlinear relationship between averaged electromyogram potential and muscle tension in normal subjects." *Arch. Phys. Med. Rehabil.* 50:613-620, 1969.
39. Zuniga, E.N., X.T. Truong, and D.G. Simons. "Effects of skin electrode position on averaged electromyographic potentials." *Arch. Phys. Med. Rehabil.* 51:264-272, 1970.