QUANTIFICATION OF MUSCLE FATIGUE: AN OVERVIEW

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In the past twenty years, physical educators, physiologists and psychologists have utilized a variety of methods and techniques for the quantification of muscle fatigue. The purpose of these methods is not merely to quantify muscle fatigue, but to assess the physiological status of muscle tissue in order to facilitate a greater understanding of the physiological mechanisms underlying muscle fatigue.

Force-time Curve. The force-time curve is a sigmoid shaped curve representing the static force produced by the muscle over a period of time. Information regarding the peak force, time to maximum force, and maximum rate of force production are easily obtained from the records. In addition, the area beneath the curve or integrated force-time curve provides information concerning the total force exerted for a given period of time. This parameter is useful for determining the absolute muscular endurance.

Fig. 1. Pre and Post Fatigue Force-Time Curves

Royce (1962) analyzed the force-time curve characteristics of a static hand grip task for 32 male subjects before and after a fatiguing exercise bout. Analysis of the post-fatigue curve indicated a decrease in maximum force production and an increase in time to peak force (Fig. 1). Fatiguing exercise reduced the rate of force production 50% and reduced the rate of release of force 150%. Royce suggested that these changes in the post-fatigue force-time curve were possibly indicative of migration of activity to other muscles and/or accumulation of metabolites in the muscle tissue resulting from fatiguing exercise. However, the force-time curve provides no direct assessment of these factors.

The integrated force-time curve has been widely utilized for quantification of absolute muscle endurance (Tuttle, et al, 1950; Burke, et al, 1953). In these studies, the subjects are required to maintain maximum muscle contraction for given time intervals. The average strength produced during the time interval is a function of the subject's maximum strength, maximum rate of force production and endurance capabilities of the muscle tissue. It is well documented that the absolute endurance of the stronger subject is superior to that of weaker subjects (Tuttle, et al, 1950; Caldwell, 1964; Start and Graham, 1964; McGlynn, 1968).

Muscle biopsy. Muscle biopsy involves the extraction of minute samples of muscle tissue (usually 10-20 mg). The specimen is generally frozen in liquid nitrogen prior to biochemical and histochemical analyses. This technique has not been widely used with human subjects since samples of muscle tissue are irreplaceable, and it is doubtful that mature muscle cells are capable of reproduction. However, much knowledge concerning the chemical status of the tissue may be determined through muscle biopsy.

Funderburk, et al. (1972) determined the concentrations of adenosine triphosphate (ATP), creatine phosphate (CP) and lactate in the quadriceps muscle of five male subjects prior to and at the termination of a fatiguing exercise bout. Fatigue was induced by exerting forces which ranged from 15-90% of maximum voluntary contraction (MVC). Only small changes in ATP concentration were noted. In contrast, the depletion of CP and lactate accumulation were greatest at 30 to 50% MVC, thus indicating that both CP and lactate may play a significant role in the development of muscle fatigue at these levels of tension.

Spande and Schottelius (1970) stimulated mouse soleus muscle tetanically for a one second period at 20 second intervals for three hours. A linear relationship between terminal CP concentration and terminal tension was noted. It appears that the breakdown of CP is a primary factor in the development of fatigue.

Edwards, et al (1972) utilized muscle biopsy techniques to determine the relationship of muscle temperature to relative endurance in ten male subjects. Muscle specimens were taken prior to, during and immediately following an endurance task (series of seven contractions at 66 2/3% MVC). ATP content was reduced to 80% of the resting value following the

exercise bout. CP also decreased 23% from the resting value after the first contraction in the series. Muscle temperature affected the depletion of high energy stores and the accumulation of metabolites, and appears to have a biphasic effect on endurance time for sustained static contractions at 66 2/3% MVC.

In short, muscle biopsy may be a useful tool for evaluating the biochemical status of muscle tissue and for providing information concerning metabolic changes in the muscle associated with fatigue.

Rating Scales. A number of rating scales have been devised for subjective estimation of pain intensity during fatiguing exercise bouts (Caldwell & Smith, 1966; Lloyd, 1971). Generally, each scale represents interval estimation of pain intensity ranging from "no discomfort" to "intolerable pain".

Caldwell and Smith (1966) noted with increasing work loads that there was a progressive increase in the rate of pain development. In addition, artificial occlusion of the blood supply to the working muscles accelerated the development of pain. Thus, subjective estimation of pain intensity may be related to the accumulation of metabolic wastes in the muscle tissue.

Fig. 2. Pain Intensity-Time Curve

Pain intensity ratings appear to parallel the development of muscle fatigue, and provide the researcher with a tool for assessing the endurance capacity of the muscle tissue. In this way, the problem of eliciting an all-out performance to task termination is partially alleviated since an approximation of the total endurance time may be estimated via visual inspection of the pain-intensity-time curve (Fig. 2).

Electromyography. The muscle action potential plays a vital role in the electro-chemical coupling process

which produces muscle contraction. Muscle action potentials are produced via mechanical, chemical or electrical stimulation of the muscle cells. The surface electromyogram (EMG) is a recording of the cumulated action potentials of the muscle fibres. A positive relationship between the force of muscle contraction and the surface EMG during voluntary muscle contraction has been established (Lippold, 1952; Close, et al, 1960; deVries, 1968a).

Quantification of the raw EMG signal is quite tedious and time consuming without the aid of electronic devices, such as, frequency counters (deVries, 1968a), integrating circuits (Inman, et al, 1952; Gregg and Jarrad, 1958; Weiss, et al, 1972) or frequency analyzers (Lindstrom, et al, 1970). All of these devices have proven quite satisfactory for quantification of EMG.

It is well documented that electrical activity of the muscle progressively increases with time during fatiguing exercise induced statically (Bourguignon, 1959; Eason, 1960; Lippold, et al, 1960; Poudrier and Knowlton, 1964; deVries, 1968b; Lloyd, et al, 1970) and dynamically (Knowlton, et al, 1951; Zhukov, et al, 1959). The progressive rise in integrated EMG during the time course of fatigue is due primarily to an increase in amplitude of the EMG, as opposed to an increase in frequency. A number of speculations regarding this rise in integrated EMG includes the firing of high threshold motor units (Knowlton, et al, 1951; de Vries, 1968b), synchronization of firing of motor units (Knowlton, et al, 1951; Lippold, et al, 1960), recruitment of motor units from fasciculi of the same muscle (Knowlton, et al 1951; Eason, 1960; Lippold, et al, 1960), increased frequency of firing of motor units (Lippold, et al, 1960) or muscle tremor caused by irradiation of electrical activity to antagonistic muscles (Lippold, et al, 1960; Person, 1960).

In contrast, some investigators have noted a decrease in the muscle's electrical activity during fatigue (Naess and Storm-Mathisen, 1955; Stephens and Taylor, 1972). This observation may be due to migration of activity to synergistic muscles which compensate for the reduced tension production of fatigued muscle fibres. Naess and Storm-Mathisen (1955) suggested that neuromuscular depression, or a reduction in impulse transmission at the neuromuscular junction, may serve to protect the muscle cell from exhaustion and, therefore, would account for the decrease in muscle electrical activity. deVries (1968a) stated that an increase or decrease in electrical activity of the muscle may be a function of the type of surface electrodes utilized. Bipolar electrodes, as opposed to unipolar electrodes, sample the electrical activity of a smaller group of muscle fibres. Therefore, one is more likely to observe a reduction in muscle electrical activity with bipolar electrodes since the electrical activity of single motor units is characterized

by a decreased amplitude during fatigue (Lindsley, 1935; Bigland and Lippold, 1954; Lippold et al, 1960).

Differences in experimental protocol, recording equipment, type of electrodes, placement of electrodes, and methods of quantifying EMG may affect the activity pattern of EMG during fatigue. Hence, discrepancies in research findings will ensue until standardized methods, techniques and instrumentation are developed.

Fig. 3. Relationship of Integrated EMG to Time for Various Relative Endurance Tasks

In addition, psychological factors may influence the pattern of EMG activity of the subjects during absolute and relative endurance tasks (Poudrier and Knowlton, 1964). However, simultaneous recording of the force output and integrated EMG has been used to determine if the subject's effort is maximal. This is based on the assumption that integrated EMG progressively increases during fatiguing exercise. Poudrier and Knowlton (1964) formulated the force/voltage ratio (F/V) and monitored changes in F/V for given time intervals during static endurance tasks. During an absolute endurance test, in which the subject is required to exert maximum force for a given period of time, the force will progressively decrease, but the integrated EMG activity or voltage output of the muscle will remain the same. Hence, if the F/V ratio increases or remains the same, the subject is not working at his maximum capability in most cases, and he may be classified, in a sense, as poorly motivated (Poudrier and Knowlton, 1964). Likewise, for relative endurance testing, in which the subject exerts a given percentage of maximal strength, the F/V ratio may be expected to decrease progressively as a function of

increased EMG activity, providing the exerted force remains relatively constant. Plotting integrated EMG as a function of time will also provide some insight into the endurance ability of various muscle groups. The slope of the resulting curve determines the rate of increase in EMG activity. This information may be used as a measure of muscle impairment with the steepest slope indicating a faster rate of muscle fatiguability (Eason, 1960) (Fig. 3). If EMG activity is plotted as a function of tension, the slope of the curve relating voltage to tension may be regarded as a measure of the efficiency of individual muscle fibres (Lenman, 1959; deVries, 1968a) (Fig. 4).

Fig. 4. Relationship of Integrated EMG and Tension for Various Levels of Maximum Strength

Another means of quantifying EMG activity is through the use of electronic counters which determine the frequency of firing of muscle action potentials. Some investigators have noted a decreased frequency of EMG signals during muscle fatigue, even though the integrated EMG progressively increased (Scherrer and Bourguignon, 1959; Person, 1960). This phenomenon may be due to failure of the neuromuscular junction to transmit impulses to the muscle cells (Naess and Storm-Mathisen, 1955), changes in central impulsation to motoneurons (Person, 1960), synchronous firing of motor units (Scherrer and Bourguignon, 1959; Lloyd, 1971), and/or recruitment of high threshold motor units which characteristically fire in a lower frequency range (Kadefors, et al, 1968; Lloyd, 1971).

A more sophisticated approach to quantification and analysis of the EMG signal is the use of frequency analysis or spectrum analysis. Briefly, this method subdivides a complex electrical signal into basic components which occur in pre-selected frequency bands. The amplitude of the components in each frequency band is called the power. When the power is plotted against the frequency bands, the resulting histogram is called the power spectrum (Chaffin, 1969). EMG frequency may range from 20-10,000 cycles/second (Ragoff and Reiner, 1961), with a normal frequency range between 40 and 50 cycles/second. The normal frequency of EMG is called the Piper rhythm or carrier frequency (Kadefors, et al, 1968). Low threshold motor units fire in a high frequency range, whereas high threshold motor units fire in a low frequency range, usually less than 40 cycles/second (Kadefors, et al, 1968).

Use of frequency analysis of EMG has substantiated many of the speculations concerning physiological adjustments during the course of muscle fatigue. An increase in the electrical activity in low frequency bands (4-30 cycles/second) is indicative of recruitment of high threshold motor units and loss of motor units firing at

high frequencies. Thus, at some point during the fatiguing exercise, a frequency shift is observed. Lloyd (1971) suggested that the frequency shift may accompany arterial occlusion and metabolic depletion of muscular energy stores. Kadefors, et al. (1968) observed a progressive decay in EMG rhythm during the course of fatigue, and noted that muscles which showed a small high frequency decay also exhibited a faster rate of recovery from fatigue. In short, the information obtained from frequency analysis of EMG provides some insight into the physiological mechanisms underlying muscle fatigue.

Summary and Comments. An attempt has been made to present a few of the various methods and techniques available to researchers and practitioners for the study of muscle fatigue. Hopefully, this information will be useful to the researcher in selecting appropriate means of quantification. These methods and techniques, used both singly and in combination, have provided valuable information regarding physiological phenomena associated with muscle fatigue. However, it is necessary to always be mindful of new technological advances and their possible applications.

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