FATIGUE IN SELECTED LOWER LIMB MUSCLE GROUPS WHILE WALKING IN A FULL PRESSURE SUIT

A Dissertation

Presented to

The Faculty of the Department of Psychology

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Philosophy

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by

John W. Dyck, Jr.

December, 1974

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ABSTRACT

The purpose of this research was twofold; first the purpose was to use the technique of frequency analysis to interpret EMG signals generated in an operational situation which involved isotonic exercise to develop baseline indexes of local muscle fatigue and, second, to fill descriptive gaps about changes in the EMG signal as selected muscle groups were exercised to develop fatigue. A unique combination of exercise, electrodes, muscle groups, and analysis were used to capture EMG signals from the thigh and calf muscle groups with surface electrodes while each of four subjects walked with and without a full pressure suit at 1 mph, 2 mph, and 3 mph. The purpose of the full pressure suit was to load the selected muscle groups and to provide muscle fatigue data from loaded muscles for comparisons with muscle fatigue data from unloaded muscles. The captured EMG signals from the selected muscle groups were recorded and analyzed with the frequency analysis technique to provide the percentage of EMG power in a low, broad frequency band (3-30 Hz).

Results of the non-parametric statistical analyses and graphic comparisons showed the individual activity of the muscle groups and the interdependent relationships between the effect of walking speed and suited or unsuited conditions on each muscle group. These relationships were interpreted from the patterns of EMG percentages in the time-series

samples taken at five-minute intervals during each 15-minute exercise trial.

The individualized activity of each muscle group is dependent on the walking speed and whether the walking speed was accomplished in the suited or unsuited condition. The muscle activity, as measured by EMG percentages, can be easily differentiated into suited and unsuited conditions at 1 mph, less easily at 3 mph, and cannot be differentiated at 2 mph. The EMG percentages differentiated the activity of the muscle groups at each walking speed for the suited calf and thigh muscle groups and the unsuited thigh, but the results for the unsuited calf muscle group were not as obvious. The results for the unsuited calf at each walking speed were mixed, i.e., the different walking speeds were not distinguished by different patterns of EMG percentages. There was not a definite pattern of the highest and lowest EMG percentages at the different walking speeds, i.e., neither the calf nor thigh muscle groups consistently generated the highest EMG percentages across the three walking speeds and/or the suited and unsuited conditions.

The original operational definition of muscle fatigue, which focused on an EMG power shift at the onset of muscle fatigue, was altered in favor of an operational definition that used the largest EMG percentage to indicate muscle fatigue. By using the largest EMG percentage as a criterion for muscle fatigue, several relationships evolved between the independent variables to give an indication of muscle fatigue which, for the EMG data collected in this research, was not available with the original operational definition. The largest EMG percentage showed that the thigh and calf muscle groups fatigued at different rates with the calf muscle group fatiguing before the thigh muscle group. Also, both muscle groups fatigued in the suited condition before they did in the unsuited condition. The largest EMG percentage showed different rates, or times, at which muscle fatigue occurred for each walking speed, e.g., at 1 mph fatigue occurred after approximately 12 minutes of exercise for both the unsuited calf and thigh, but after seven minutes and five minutes for the suited thigh and calf, respectively. At 2 mph, the suited and unsuited thigh fatigued after 15 minutes of exercise, the suited thigh after ten minutes, and the suited calf after approximately seven minutes of exercise. Then, at 3 mph, the unsuited calf and thigh fatigued after ten minutes of exercise, the suited thigh after seven minutes, and the suited calf after five minutes of exercise.

From a different perspective, fatigue occurred after about seven minutes of exercise for the suited thigh at 1 mph, the suited calf at 2 mph, and the suited thigh at 3 mph. There was no difference in the time of fatigue for the unsuited calf at 2 mph, or the unsuited calf and unsuited thigh at 3 mph. The unsuited calf and thigh fatigued after approximately 12 minutes at 1 mph and the suited and unsuited thigh at 2 mph.

These rates of fatigue indicate that, generally, the onset of fatigue occurred earlier at 1 mph and 3 mph than at 2 mph. At first this result may appear contradictory, but all the subjects agreed that walking at 2 mph was the most comfortable, natural pace, while walking at 1 mph was unnatural and awkward, and walking at 3 mph was truly "fatiguing".

It was concluded that the frequency analysis technique is an operationally feasible, and valuable, tool for interpreting the complex interference pattern of the electromyogram from muscles involved in isotonic exercise for the purpose of describing the onset of local muscle fatigue, and detailing rates of local muscle fatigue.

Future research using the frequency analysis technique should investigate two parallel paths. The first would be to further develop the exploratory/baseline muscle fatigue data from this research with more elaborate research designs which include frequent time-series sampling to further detail the onset of muscle fatigue and delineate levels of muscle fatigue. The second, and parallel, research effort should attempt to find the behavioral correlates that accompany various levels of muscle fatigue in the hope of providing useful information to industrial designers that will help them predict the onset of muscle fatigue.

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CHAPTER I

INTRODUCTION

Purpose

Voluntary muscle contractions are accompanied by electrical activity that is a series of muscle action potentials (MAPs) called myo-potentials. A recording of these myo-potentials is called an electromyogram (EMG). During voluntary muscular contraction, the myo-potentials occur at different rates depending on the frequency at which the motor units fire. Some of the myo-potentials overlap resulting in a complex interference pattern in the EMG. To interpret the EMG, the interference pattern has to be separated into its primary and secondary components so that the muscle activity can be analyzed.

The primary components of the EMG, viz., amplitude, duration, and waveform pattern; are separated and developed through an electronic process called integration. The secondary components, viz., EMG power in specific frequency bands and phase shift alternations; are separated out of the complex interference pattern with a process called frequency analysis. The secondary components seem to reflect the onset of muscular fatigue more than do the primary components. For example, a number of researchers (Chaffin, 1969a, 1969b; Kogi & Hakamada, 1962; Kaiser & Peterson, 1963, 1968; and Sata, 1965) have used the frequency analysis technique to separate the myo-potentials in the EMG interference pattern into the secondary components of frequency and power. By using the frequency analysis technique these researchers have reported that during fatigue there was a shift in EMG power from high, broad frequency bands to low, broad frequency bands. But, the data which show this shift of the predominant frequency toward lower frequency bands in the frequency/amplitude (power) spectrum of the EMG signal have been produced with rather specialized methodology in contrived situations. The fatiguing task has been an isometric (contracted, non-moving muscle) exercise of short duration, usually not more than 90 seconds. The myo-potentials generated during these short exercise periods were captured by needle type electrodes and the EMG was electronically integrated for interpretation and analysis. Chaffin (1969a, 1969b) is the only researcher who used surface electrodes, exercises of up to 45 minutes, and frequency analysis instead of integrating the EMG signal; but, he used an isometric exercise for the fatiguing task.

The primary purpose of this research, then, was twofold; first, the purpose was to test the operational feasibility of using the frequency analysis technique on EMG signals generated in an actual work task to develop baseline indexes of local muscle fatigue. Secondly, the purpose of this research was to describe the change in the EMG power as muscles fatigue during isotonic exercise (moving as opposed to static exercise). The work task was to walk in a full pressure suit similar to the space suits used by the National Aeronautics and Space Administration (NASA) for extravehicular activity on the Apollo moon landing and Skylab missions. Initially, this work task may seem as contrived as those used in previous research, but suited and unsuited data were collected to compare the EMG signals from heavily loaded muscles with the EMG signals from unloaded muscles. The unsuited task was designed to compare favorably with a very common work task that has practical applications to many industrial situations, i.e., work tasks which require walking. The EMG signal from the calf and thigh muscle groups was monitored while each of the four subjects walked at 1 mph, 2 mph, and 3 mph. The walking task difficulty was increased by requiring the exercise to be performed in a full pressure suit.

Therefore, it is predicted that the frequency analysis technique will prove technically feasible for analyzing EMG signals generated during an operational work task. Based upon the research results reported by Chaffin (1969a, b), it is also predicted that the frequency analysis technique will produce different frequency patterns for the selected muscle groups. Specifically, these predicted differences are:

Hypothesis 1: The EMG signals from loaded muscles (suited condition) and unloaded muscles (unsuited condition) will have different frequency analysis patterns with the loaded muscles producing more EMG power than the unloaded muscles.

Hypothesis 2: The EMG signals will have different frequency analysis patterns at each walking speed with the faster walking speeds producing more EMG power than the slower walking speeds.

Hypothesis 3: The EMG signals at selected points in time during the exercise period will have different frequency analysis patterns with longer exercise periods producing more EMG power than shorter exercise periods.

Hypothesis 4: The frequency analysis technique will prove to be technically feasible for analyzing EMG signals generated during an operational work task.

Describing and Measuring Fatigue

Conceptual interpretations of fatigue are so general and diverse that a meaningful description is difficult. At one end of the good vs. bad continuum is the following bad example:

> "...fatigue should be assessed as an undesirable deviation from the homeostasis towards which all functions have a tendence." (Hasimoto, 1971, p. XIV)

It is proper at this point to observe the traditional and necessary warning that "fatigue is a complex phenomenon and perhaps a complex of numerous phenomena." (Basmajian, 1967, p. 76).

The term fatigue is variously used to describe motivational states of the organism associated with a need for rest (physiological fatigue), negative feeling (subjective fatigue), or any decrement in a response after repeated or prolonged exercise (objective fatigue). In addition, the term is often used to describe fatiguing situations or functions, e.g., mental fatigue, combat fatigue, pilot fatigue, and driver fatigue.

Fatigue has been studied in a variety of situations which, in turn, require different criteria for the occurrence of, or presence of, fatigue. These differing situations compound the confusion surrounding the concept of fatigue, for not only are the situations not comparable, but the onset of fatigue can also be influenced by (1) the state-of-the organism, e.g., the condition of the muscles, recency of sleep or rest, the state of health and other bodily needs; (2) psychological factors, e.g., morale interest in the task, boredom, and stress; and (3) environmental factors, e.g., levels of noise, illumination, temperature, and humidity.

Some researchers do not even bother to specify a criteria for the occurrence of fatigue. For example, Currier

(1970) in his article entitled, "Measurement of Fatigue," does not define or discuss a definition of fatigue; for him it just occurs during muscular exertion. Similarly, in their article, "Changes in the Electromyogram Produced by Fatigue in Man," Sherrer and Bourguignon (1959) make no attempt to specify a criteria of fatigue.

Biochemical and Physiological Fatigue. Generally, physiologists treat fatigue as an indicator of the accumulation of toxic substances in the blood or the exhaustion of energy reserves. However, there is not complete agreement as to the situations in which toxic substances or the exhaustion of energy reserves occur. Accompanying muscle contraction there is an increase in blood flow which brings oxygen and glycogen into the muscle to replace reserves being used for the contraction. Conversely, the increased blood flow removes the end products of the energy conversion process, e.g., lactic acid and carbon dioxide (Bartley & Chute, 1974). Under prolonged activity any one of the following may occur, (1) insufficiency of oxygen, (2) an inadequate supply of glycogen, or (3) failure to completely remove, or be able to remove the conversion end products. Consequently, research results are often confusing and contradictory when only one of the biochemical indicators is monitored, e.g., the presence of lactic acid in the venous blood, rather than all three processes.

The failure of a muscle is not limited to metabolic processes. Muscles, or muscle groups, may fail to develop tension because the nerve fibers, synapse, or muscle end plates may fail to conduct the muscle action potential. Interpretation of this action is confounded when the nerve or muscle fibers fail at different times.

In addition, there is no agreement about whether the controlling mechanism for these intricately related processes lies centrally in the nervous system or peripherally in the muscles. Possibly the metabolic changes in the muscle and/or the muscle end plates control the onset of fatigue or they may just provide feedback information to the central nervous system which could control the onset of fatigue.

Objective Fatigue. Psychologists, work physiologists, and physiological psychologists generally rely on measures of performance decrement to measure fatigue. A reduction in output is not a very sensitive or reliable measure because it is susceptible to several confounding variables, e.g., variations in behavior patterns, or an increase in effort which does not result in reduced output. These compensatory behaviors tend to mask the onset of fatigue which makes the assessment of fatigue from performance measures alone very difficult.

Subjective Fatigue. Bartley (1965), who proposes a personalistic approach to fatigue, objects to a decrement output becoming a synonym and finally a definition for fatigue. He says this makes fatigue, not a condition of the worker, but a label for what he failed to produce. Traditional studies of work, he claims, do not provide information about fatigue, only about performance decrement. Rather than using fatigue as a loose, catch-all term, Bartley (1965) separated the total fatigue situation into elements he called impairment, disorganization, discomforts which are localized in muscles, work decrement, and fatigue. Impairment is the reduced ability of the cells to function, i.e., cellular dysfunction. Consequently, Bartley would label the focus of this research muscle impairment, instead of muscle fatigue. Disorganization is a modification in the way cells, tissues, and organs work together, e.g., sensory inputs that tell the performer he is failing can change the whole pattern of nervous function without initially impairing cells. Awkwardness is an example of disorganization, skill is an example of appropriate organization. Discomfort arises through sensory mechanisms being affected by tissue changes including those called impairment. Work decrement is the "measurable drop in activity of muscles measured in energistic terms, or the drop in intellectual productivity measured in other terms" (Bartley, 1965, p. 15). Both types of decrements are usually measured in units of production.

For Bartley (1967), fatigue is a condition of the individual and should not be described in terms of external situations, e.g., work output. He goes back to the history of the word for guidance, and justification, to find fatigue had one meaning: "...the aversion toward activity and the feeling of inability to perform" (Bartley, 1967, p. 21). Consequently, Bartley & Chute (1947) chose the word's original meaning and defined fatigue as the sensory-cognitive syndrome which includes tiredness, aversion to work, body discomfort, and ineffectiveness in performance.

Mental Fatigue. It is generally acknowledged that a person engaged in intellectual work, although overtly quiet, may show deterioration in performance and experience increasing weariness. Yet, the metabolic cost of the mental activity is small. Actually, what is labeled mental fatigue does not produce identical symptoms to those of physical exhaustion. Granted, both lead to an increase in errors and accidents, an increase in performance variability, and increased irritability and loss of self-control, to name just a few. Yet, for mental fatigue, these same symptoms may reflect boredom, satiation of attention, or a conflict of interest with other activities. Additional support for the two different processes comes from their respective recovery profiles. The recovery of mental fatigue is closely associated with shifts in attention, different problem solving strategies, or other similar processes not directly associated with the products of muscle fatigue.

Measurement of Fatigue. As might be expected, because of the diverse types of fatigue, the diverse backgrounds of those doing research on fatigue, and different levels of explanation, there is little correlation of measures across, or within, fatigue criterion conditions.

Performance decrement, even with its limitations, can be used as a crude index of objective fatigue, provided one is interested in output, per se. Errors, accidents, reduced output, deterioration of coordination, or organization might be better indicators of the disruptive effects of fatigue rather than the presence of fatigue. Together they might reveal a comprehensive picture of the fatigued state, but, as yet, no useful index, or formulae for weighting their individual contributions has been developed.

A number of physiological and neuroendocrine indicators have been used as measures of fatigue, but they do not offer consistent results across different criteria, or even reliable results across the same criteria. Typical measures have been basal metabolic rate, pulse rate, critical flicker fusion frequency, eye-blink rate and EEG, body temperature, pupillary reactions to light, galvanic skin response, oxygen uptake, venous blood lactic acid content, and blood pressure.

The previously mentioned physiological and neuroendocrine indicators are used to measure global, whole body, or general fatigue. Another set of measures that are of particular interest to the focus of the present research have to do with local fatigue, i.e., fatigue in selected muscles or muscle groups. In this respect, measures of local fatigue that seem to have the most potential are those measures that use the muscle action potential. These techniques monitor the myo-potential from selected muscles or muscle groups. The resultant EMG is analyzed and interpreted for parameter changes that coincide with the incident of fatigue. But, as before, the absence of a standardized criterion for the onset of fatigue results in unreliable and nongeneralizable research findings.

CHAPTER II

BACKGROUND AND STATUS OF EMG RESEARCH

Quantification of the EMG

The electromyogram (EMG) is a recording of the electrical action potentials (MAPs) which occur in the muscle and are called myo-potentials. Several researchers (Inman, et. al., 1952; Close, 1960; deVries, 1965; Troup and Chapman, 1972) have attempted a variety of methods of quantification to increase the interpretability of the EMG. Basically, these techniques center around methods to interpret the interference pattern, how to separate the interference pattern into its components, and what components or combination of components are important for various interpretations. These interpretations are used in clinical diagnosis of myopathies, to develop prosthetic devices, in kinesiological research, and to study the characteristics of muscular activity. The parameters of the EMG available for quantification are amplitude, frequency, and duration of the myo-potentials.

Some type of electrode is required to capture the EMG signal. These electrodes may be monopolar or bipolar electrodes placed on the skin's surface (surface electrodes) or inserted under the skin's surface into the muscle itself (needle type electrode). The choice of electrode type depends on the interpretation and/or application desired.

If isolation of the muscle is required, or if the myo-potentials of deep-lying muscles are to be investigated, needle type electrodes are necessary. But, special medical training is required to insert the needle electrodes which limits their use to special situations. Surface electrodes can be applied easily, but they pick up myo-potentials from a large area, and so are best suited for the study of muscle groups. Therefore, needle and surface electrodes sample myo-potentials from different populations which result in different data.

Once the EMG signal has been captured by the electrode, the signal has to be amplified and recorded. Amplifiers and pre-amplifiers that have been used to amplify the EMG signal captured by the electrodes have different frequency responses and sensitivities. The amplified signal is generally displayed on an ink type strip chart or an oscilloscope for analysis by visual inspection, or recorded on magnetic tape for computer assisted analysis.

The continued contraction of a muscle is accompanied by electrical activity and with an increase in loadings, or with the presence of fatigue, there is a change in the electrical activity which is reflected in EMG changes. There are no universally approved methods for scoring/analyzing the changes in the EMG and, as a result, many different methods have been devised to quantify the EMG. All these strategies attempt to describe the EMG in terms of the basic parameters of amplitude, frequency, duration, and wave form which then can be subjected to statistical treatment for interpretative assistance.

The EMG changes have been the subject of numerous studies. Most of these studies observed changes in an integrated EMG instead of analyzing the myo-potentials directly, i.e., in its unintegrated form. The interference pattern of a directly recorded myo-potential is very complex which makes it difficult to analyze anything other than some kind of peak-to-peak amplitude count. This type of analysis is of little analytic value except to indicate the concurrent actions of several muscles during a movement, or to indicate which muscles are involved in various movements.

A certain degree of quantification can be achieved by integrating the myo-potentials. The integrated recording is the result of electronic treatment of the electrical signals so that frequency, duration, and amplitude of the myo-potentials are averaged. The integrated signal gives an envelope of the amount of electrical activity produced during a particular activity or contraction.

Other strategies have included counting the frequency of spikes, measuring the interval between spikes, measuring the duration of muscle unit action potentials, averaging the EMG amplitude over predetermined periods, using the highest amplitude at a given time during a given moment, or using the frequency and amplitude from the interference pattern separately and in combinations. There is no rationale for some of these techniques other than that they are different.

The most common method utilizing frequency, amplitude, and duration is to integrate the myo-potentials with electronic treatment of the signal. Integration amalgamates the simultaneous variation of frequency, duration, and amplitude into a single measure. The area under the curve formed by the integration procedure is specified in EMG units. Some investigators have converted the integrated signal into pulses whose frequency of occurrence was proportional to the magnitude of the interference pattern (deVries, 1968; Currier, 1970). The frequency output could then be counted for digital presentation.

The development of new technical equipment and computer analysis has simplified investigative methods and overcome the drawbacks of former analysis techniques. The integration technique combines the frequency, amplitude and duration of the myo-potential in such a way that a lot of information is lost about what is happening simultaneously in each parameter. Techniques that focus on frequency or amplitude individually have had minimum success. The development of frequency analyzers to produce power spectrums has greatly increased the utility of EMG data by giving a more quantified representation of myo-potential interference patterns. The frequency analysis technique divides the complex interference pattern into its basic frequency and amplitude components. The result, called a power spectrum, is the amplitude in each selected frequency band. This type of information was not available prior to use of frequency analysis.

The EMG and Muscle Fatigue

Research reports of comparative value and applicable to the focus of the results reported from this research were those studies which evaluated muscular fatigue by capturing the myo-potentials with surface electrodes and analyzing the resultant EMG with a frequency analysis technique. Some of the results from integration techniques were of comparative interest. But, those research reports on the clinical uses of the EMG, or the EMG relationships between muscle, tension, and force were of no direct interest.

Despite the extensive research into the neural basis for the EMG changes as the muscle fatigues, there is a general lack of agreement about the specific processes involved. The change in electrical activity may be of a spinal cord origin, a sychronization of myo-potentials, augmentation of the amplitude and duration of potentials, an increase in polyphasic potentials, a result of firing a new set of motor units or an increase in the frequency of firing for the same set of motor units, or both (Basmajian, 1967, 1972).

The neural basis of the EMG was only of tangential interest to this research. Of primary interest was the different reports of what happens to the EMG during and after the onset of muscular fatigue. Seyforth (1940), Linquist (1959), and Travis and Lindley (1931) agreed that progressive fatigue was accompanied by a decrease in the amplitude of the myo-potentials when recorded and analyzed directly. Yet, Zhukov and Zakharants (1960), and Merton and Pampiglione (1950) reported the amplitude of the potentials rose with progressive fatigue during isometric exercise of the biceps and triceps and that the integrated level of voltage also arose.

Gregg (1958) recorded changes in the myo-potentials with surface electrodes under conditions of repeated or continuous performance of a motor task. He found that reports of subjective fatigue correlated with an increase in the integrated potentials after prolonged work. There were also pronounced differences in the mean value of the integrated myo-potentials recorded from different muscle groups. Lippold <u>et. al.</u> (1960), using surface electrodes and integration, reported that as a voluntary contraction progresses, the electrical activity from the muscle increased. They also reported that for voluntary contractions at a given, constant tension the integrated myo-potentials recorded from whole muscles gradually increased. These researchers did not define, operationally or otherwise, the onset of fatigue at any specific change in the characteristics of the integrated EMG. They just described the progressive changes. Similarly, Missiuro (1962), and Tomita (1939) reported that the integrated EMGs from surface electrodes over the biceps and triceps grew with fatigue. Then Sloan (1965) reported that the electrical activity recorded from fatiguing rectus femoris muscles showed an EMG amplitude increase but not consistent changes in frequency.

For muscles fatigued by prolonged isometric contraction, the relationship between voltage and tension remained linear but was a steeper slope than the linear relationship that existed prior to fatigue, i.e., more electrical activity was associated with a given tension in the fatigued state (Edwards & Lippold, 1956). Scherrer & Bourguignon (1957) stated that total electrical activity per second during an initial maximum contraction was considerably less than in the same muscle after work, i.e., the integrated EMG and the isometric tension were inversely related. They also suggested that there was a difference between the fatigue of repeated maximum effort and that of continuous contraction.

As previously mentioned, the reason for the variety of results reported by different investigators was a lack of standardization in methodology, e.g., different types of electrodes and electrode placement, different exercises, and different ways of interpreting the total electrical activity of the integrated EMG. Scherrer, et. al. (1959) explained that the arbitrary EMG units may be expressed as the quantity of integrated electrical activity of each movement (Qmvt), or the quantity of integrated electricity of the movement per unit time (Qmvt/sec.), or the quantity of the integrated electricity per second during maximum effort (Qmax), or the integrated quantity during maximal effort per Kg. of force (Qmax/kg), or the integrated quantity per second for an isometric contraction of constant force (Qstat).

In order to avoid this confusion and further quantify the integrated EMG, Currier (1970) used deVries (1968) method of treating the integrated signal with a voltage-to-frequency converter. The pulsed frequency output of the converter was proportional to the quantity of electrical activity which could then be counted to produce a digital measure. The results supported the general results of previous EMG/fatigue research, i.e., electrical activity increased as the anterior deltoid muscle fatigued.

Frequency analysis has been used to produce the power spectrum of recorded myo-potentials during isometric contractions (Walton, 1952; Hayes, 1960; Kaiser & Petersen, 1965; Scott, 1967). The advantage of using power spectra to analyze myo-potentials in the EMG, instead of an integrated EMG, is an increase in quantitative precision. The research investigations using the integrated EMG talked about "total electrical activity" in arbitrary EMG units. Frequency analysis specifies this "total electrical activity" in terms of the main frequency components, i.e., it separates the EMG into the power, or amplitude, for selected frequencies or frequency bands.

Changes in the frequency spectrum of surface EMGs during isotonic muscle fatigue was first studied by Kogi & Hakamada (1962) who demonstrated an increase of amplitude in the low-frequency region. Kaiser & Petersen (1963) and Sato (1965) observed a complimentary decrease in high-frequency amplitude during muscle fatigue. The low-frequency increase and high-frequency decrease was again verified in several muscles with the employment of a standardized experimental and analytical technique by Kadefors, Kaiser, & Petersen (1968).

Isometric and isotonic exercises have been used to study electrical changes in whole muscle groups, (Lippold, Redfearn, & Vuco, 1960). The myo-potentials were captured with surface and needle electrodes and the resultant EMG was analyzed with narrow band integration to simulate a primitive frequency analysis. Although the primary purpose of this study was muscle tension, the authors reported that as voluntary contraction progressed, the electrical activity recorded by needle and surface electrodes increased. Their primitive frequency analysis technique showed peak electrical activity between 6-15 Hertz (Hz) after a fatiguing contraction.

The reported low-frequency increase and high-frequency decrease in the EMG during muscular fatigue, as revealed by frequency analysis, provided the framework for Chaffin's (1969a, b) application of these results to local muscle fatigue in industrial human performance. The frequency shifts toward lower frequencies were related to subjective and objective assessments of fatigue. The fatiguing task was to hold weights slung over the wrist. Two broad bands were defined by which the degree of shift could be measured. The low band was from 4-30 Hz and the high band was from 60-100 Hz. The rate at which fatigue developed accelerated with increasing loads. A five pound wrist load resulted in fatigue at about one-half the rate produced by a 10 pound weight, one-fifth the rate produced by a 15 pound weight, one-tenth the rate of a 20 pound weight, and one-twentieth the rate produced by a 25 pound weight. Chaffin's procedures and results are closely related to the current research effort reported here.

CHAPTER III

METHOD

General

Previous research on muscle fatigue has generated data from different isometric exercises, used different processes for integrating the EMG signal, interpreted different parameters of the integrated EMG, and used different types of electrodes and electrode placement. Very little data is available in which the EMG is analyzed by frequency analysis and none for an EMG generated during isotonic exercise.

Therefore, this research was designed to fill in some of the descriptive gaps about muscle fatigue and to extend the technique of frequency analysis to EMG signals generated in an operational situation which involved isotonic exercise. The unique combination employed was the use of surface electrodes to capture myo-potentials from the calf and thigh muscle groups involved is isotonic exercise and to analyze the resultant EMG with the frequency analysis technique to describe the development of muscle fatigue during the performance of an operational task.

For this research, the independent variable, i.e., those variables which were deliberately manipulated to find out the affect of the manipulations, were the muscle groups (calf and thigh), walking speeds (1 mph, 2 mph, and 3 mph), conditions (suited and unsuited), and time-series samples (after 5, 10, and 15 minutes of exercise). The dependent variable, i.e., the criterion, or the variable which was to be measured, was the myo-potential as recorded by the EMG. For the purposes of this research, fatigue was operationally defined as: Muscle fatigue occurs when, during a prescribed work task, the EMG power in a low, broad frequency band increases. The low, broad frequency band used for this research was the 3-30 Hz band.

Subjects

All space suits are "custom-fitted" for a specific person, which in this case is an astronaut or an astronaut-like person. This custom-fit is required to maximize mobility and minimize the discomfort of the person using the space suit. Therefore, as a minimum requirement, the subjects used in this research had to be as close anthropometrically as possible to the astronaut for whom the space suit was built.

In addition to the anthropometric criteria, each subject had to:

1. Be a volunteer.
2. Be less than 35 years of age.
3. Have a current Class III Flight Physical examination and current altitude chamber training.

Using the above criteria, four University of Houston students were selected as subjects for this study. Each subject was sized and fitted to the space suit by NASA suit personnel to insure a good, comfortable fit. This fitting was necessary to eliminate pressure points that could develop into discomforts that would, in turn, restrict walking motions.

Since the subjects had minimum suit experience, each subject was given orientation and training sessions by NASA suit personnel. Therefore, each subject had approximately two hours experience walking in the space suit prior to any data collection.

Task and Apparatus

Electromyograms of the myo-potentials from the thigh and calf muscle groups were recorded while each subject walked on a motorized treadmill at walking speeds of 1 mph, 2 mph, and 3 mph. The motorized treadmill could be adjusted to provide constant walking speeds of 1 mph, 2 mph, or 3 mph. Each subject walked on the motorized treadmill at each speed under two testing conditions, i.e., while in a shirt-sleeve condition without the space suit (unsuited) and in the space suit (suited condition).

Testing sessions consisted of exercise trials at each speed under each condition. Each session had a 15 minute trial, followed by five minutes of rest, then another 15 minute trial at the same speed and condition as the first trial. Each subject was tested at approximately the same time of day, and the same day of the week with at least six days of rest between testing sessions. This schedule provided six testing sessions for each subject, i.e., one session at each walking speed in the unsuited condition, and one session at each speed in the suited condition. The testing schedule is presented in Table 1.

The Apollo space suit used for the suited conditions is described in detail by Sheer, Kirkpatrick, and Dyck (1971). Briefly, the space suit was an A7L model Apollo suit consisting of the following components:

1. A constant-wear-garment which is similar to long underwear and designed to be worn next to the skin to absorb perspiration and enhance comfort.

2. The torso of the Apollo primary garment assembly is the suit proper and covers the body except for the head and hands. The assembly has four components, the inner liner to ease donning and doffing and to reduce the number of pressure points, the gas container which is constructed of neoprene and includes neoprene boots integral to the lower legs of the suit, a restraint assembly to provide structural support for the pressurized suit, and a protective coverlayer to protect the gas container.

3. The glove assembly in which the gas container and restraint assembly are in one unit. The gloves attach to the torso wrist with a slide lock disconnect incorporating 360° rotation.

TABLE 1

TESTING SCHEDULE

SUBJECT	TESTING DAY 1	2	3	4	5	6
A	S 1	S 2	S 3	U 1	U 2	U 3
B	S 3	S 2	S 1	U 3	U 2	U 1
C	U 1	U 2	U 3	S 1	S 2	S 3
D	U 3	U 2	U 1	S 3	S 2	S 1

Note: S = SUITED
U = UNSUITED
1 = 1 MPH
2 = 2 MPH
3 = 3 MPH

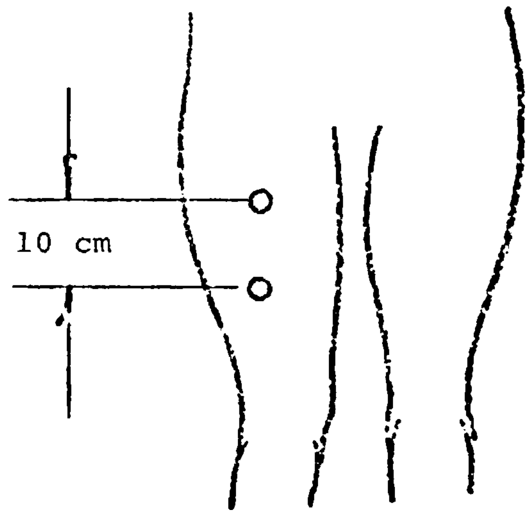
4. <u>The helmet assembly</u> consisting of a "bubble" helmet in which the protective shell and visor are combined. The helmet is attached to the torso of the suit with a neck-ring lock assembly.

5. <u>The gas distribution system</u> in the suit distributes oxygen over the body and extremities for thermal control and ventilation.

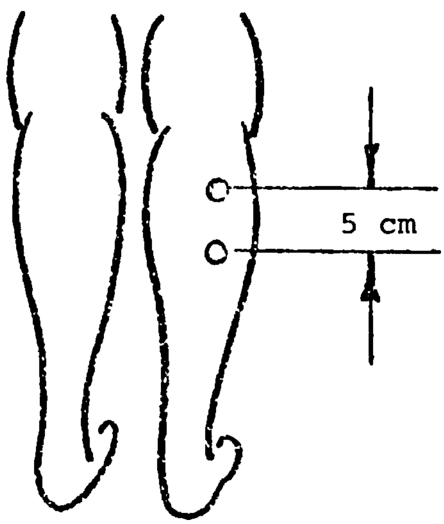
The space suit was pressurized at the standard operating pressure of 3.7 pounds per square inch.

Electromyographic Recording

While the subject was walking on the motorized treadmill, bipolar surface electrodes were used to capture the myo-potentials of the right anterior thigh muscle group and the right posterior calf muscle group (Figure 1). Two silver/silver chloride electrodes fitted with Field Effect Transistors (FETs) were placed over each muscle group spaced 10 centimeters, center-to-center, over the thigh muscle group, and approximately five centimeters, center-to-center, over the calf muscle group. The skin contact area of the electrode was approximately 1.5 square centimeters. Each electrode was housed in a plastic housing to support the electrodes and provide surface area to accommodate the double adhesive disk used to attach each electrode to the skin. The electrodes and wires were held in place by non-constricting elastic bandages which were wrapped individually around the thigh and calf.



A. RIGHT ANTERIOR THIGH MUSCLE GROUP



B. RIGHT POSTERIOR CALF MUSCLE GROUP

FIGURE 1

ELECTRODE PLACEMENT

The electrodes were connected to amplifiers which were, in turn, connected to a pen-and-ink strip chart and a 1/4 inch, seven channel, Ampex SP300 magnetic tape recorder. The analog EMG signal from the magnetic tape was converted to a digital representation by an A-to-D converter. Then, the digitized EMG was analyzed using a fast Fourier Analysis program to produce a frequency analysis for the EMG signal. A schematic diagram of the EMG monitoring and analysis system is presented in Figure 2.

The amplifiers provided a differential input impedance exceeding forty megohms in the frequency band between 0.2 and 100 Hz. The gain of the amplifiers was set at approximately 1000x.

Data Reduction

The frequency analysis of selected 15 second epochs of EMG signal was programmed to report EMG power that resided in the low, broad frequency bank of 3-30 Hz. The 15 second epochs of EMG signal selected for digitization and frequency analysis were a 15 second epoch at the start, a 15 second epoch after five minutes of exercise, a 15 second epoch after 10 minutes of exercise, and a 15 second epoch after 15 minutes of exercise. This resulted in a total of four EMG epochs from each 15 minute trial. The 15 second epochs and the broad frequency band were similar to the EMG samples and frequency band used by Chaffin (1969a, b).

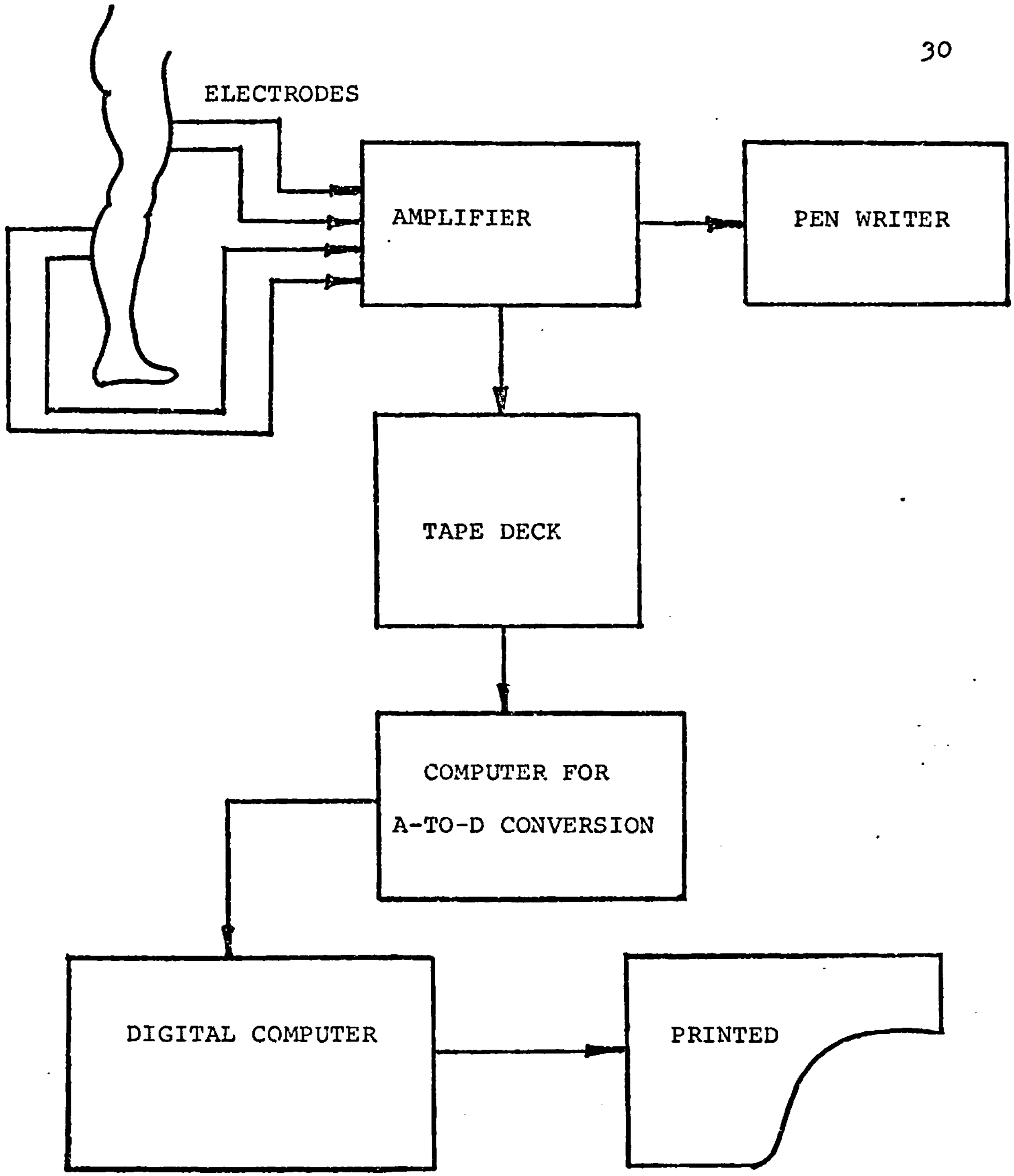


FIGURE 2

EMG MONITORING AND ANALYSIS SYSTEM

The basic data generated from the frequency analysis was the percentage of EMG power that resided in the broad frequency band during the sampled epochs. The percentage of EMG power was computed by dividing the amount of EMG power that resided in the broad frequency band of 3-30 Hz by the total EMG power that resided in the basic broad frequency band of 3-100 Hz.

Procedure

At the start of each testing session the subjects were prepared for electrode application by thoroughly cleaning the electrode sites with reagent-type acetone to remove dry skin and oils from the site. The electrodes were applied to the skin and secured with surgical adhesive tape and wrapped with elastic bandages. System continuity and baseline measures were then taken. If the scheduled testing was for the suited condition, the subject donned the space suit and the suit was pressurized to 3.7 pounds per square inch. After verification on the electrode-amplifier-recording system continuity, the motorized treadmill was turned on and brought up to the scheduled walking speed. The suited/unsuited subject then stepped on the moving treadmill and walked at the scheduled speed for 15 minutes during which the EMG from the two muscle groups was captured, amplified, and recorded.

After 15 minutes of walking, the subject stepped off the treadmill, was seated, and rested for five minutes.

Then the system integrity was rechecked and the second 15 minute trial initiated. Each testing session lasted a total of 35 minutes, i.e., two 15 minute data collection trials plus a five minute rest period.

CHAPTER IV

RESULTS

The EMG measures used as the basic data for the following graphical presentations and the nonparametric statistical analyses were the percent of EMG power concentrated in the broad 3-30 Hz band, i.e., of the total EMG power in the broad 3-100 Hz band, that percentage of the total power which was concentrated in the narrower 3-30 Hz band.

At the beginning of each exercise period there were no individual EMG differences for each muscle group across the four subjects. This absence of individual EMG differences was determined by using the initial EMG percentages taken from each subject in the unsuited condition and analyzing them with the Kruskal-Wallis one-way analysis of variance (Siegel, 1959). The Kruskal-Wallis test was used even though the samples may not have been completely independent. A separate analysis was performed using the initial measures taken in the suited condition. No significant differences were found between the subjects in either condition which indicates that the initial EMG measures represented one population, not different populations.

There were no significant differences in the initial EMG percentages for each subject on different testing days. The absence of day-to-day differences was determined by matching the initial EMG percentages in the unsuited condition with the initial EMG percentages in the suited condition for each muscle group and analyzing the differences according to the Wilcoxon matched-pairs signed-ranks test (Siegel, 1956). The Wilcoxon test was used even though the samples may not have been completely independent. No significant differences were found between the subjects in either condition which indicated that the initial EMG measures represented one population, not different populations.

Samples of the EMG were taken at four points in time during each 15 minute exercise trial, viz., at the beginning or zero point, at the five minute point, at the ten minute point, and at the end, or 15 minute point. The Friedman one-way analysis of variance test (Siegel, 1956) revealed a significant difference in the EMG percentages at these points in time for calf muscle group ($p < .05$) and the thigh muscle group ($p < .01$).

Each testing session consisted of two 15 minute trials at the walking speed and under the condition scheduled for that day's testing. No significant difference was found between trials A and B using the Wilcoxon matched-pairs signed-ranks test (Siegel, 1956). This absence of a statistically significant difference between trials A and B indicated the five minute rest period between the trials was sufficient to restore the EMG to the baseline level.

The three independent variables analyzed for their individual effects were: (1) muscle groups (calf and thigh);

(2) conditions (suited and unsuited); and (3) walking speeds (1 mph, 2 mph, and 3 mph). The non-standard use of the Wilcoxon matched-pairs signed-ranks test (Siegel, 1956) to test the individual effects of the muscle groups and conditions was justified because the samples were interpreted to have been independent and uncorrelated.

In addition, there were no EMG measures available for the 15 minute sample in the suited condition at the walking speed of 3 mph because the subjects complained saying they were physically exhausted and unable to continue after walking for ten minutes in the pressure suit at 3 mph.

The EMG measures displayed in Figures 3 through 12, are grouped into five sets with each set representing a coherent combination of independent variables. The graphs are ordered in the following manner:

Figures 3, 4: thigh and calf at 1 mph

Figures 5, 6: thigh and calf at 2 mph

Figures 7, 8: thigh and calf at 3 mph

Figures 9, 10: thigh at 1, 2, and 3 mph

Figures 11, 12: calf at 1, 2, and 3 mph

These five sets of graphs portray the percent of EMG power concentrated in the 3-30 Hz band during the first 15 minutes trial (labeled A) and the second 15 minute trial (labeled B) of each exercise period plotted at three points in time on the abscissa against the percentages on the ordinant. The

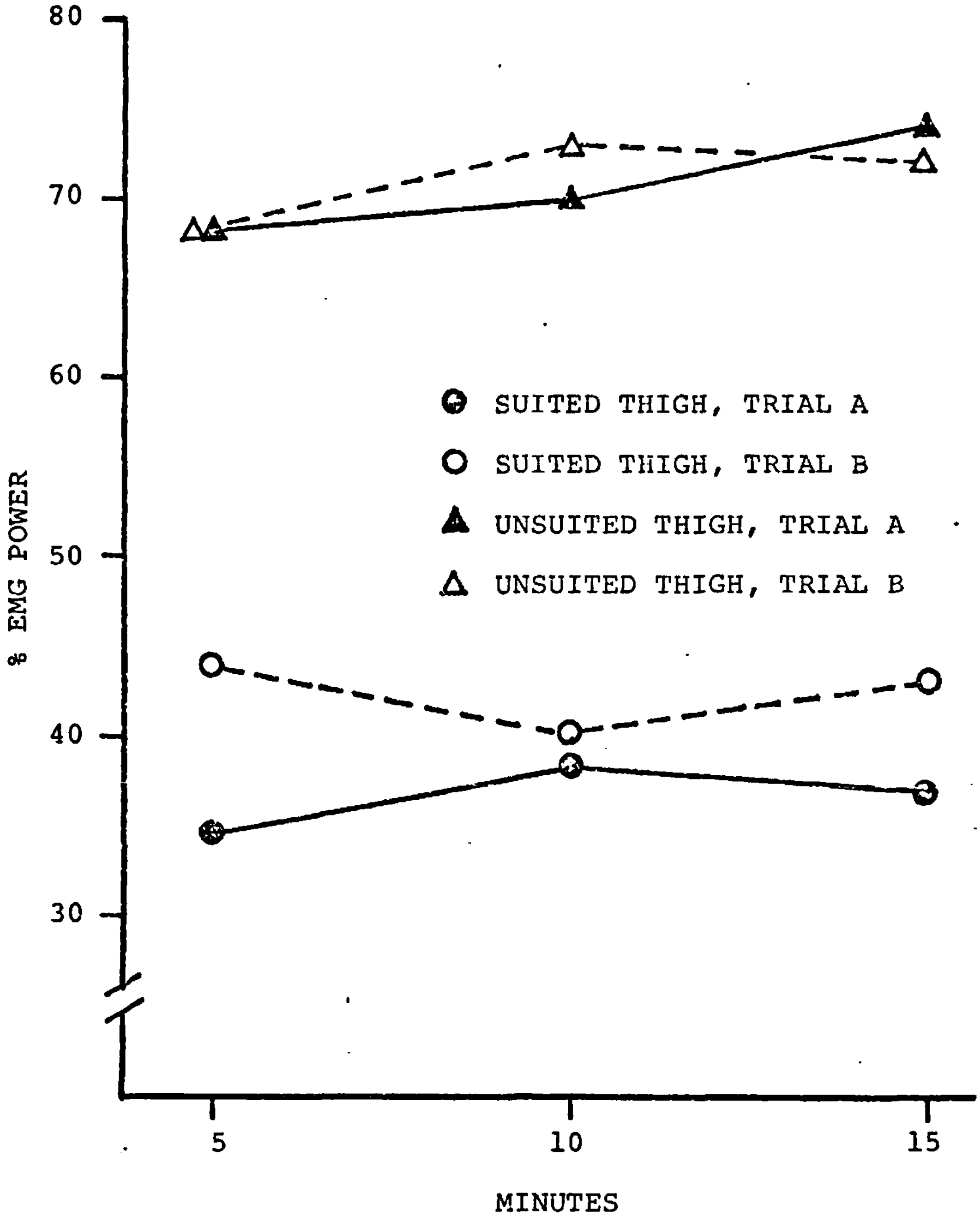


FIGURE 3

PERCENT OF EMG POWER IN 3-30 HZ BAND

FOR THE SUITED AND UNSUITED THIGH

WHILE WALKING AT 1 MPH

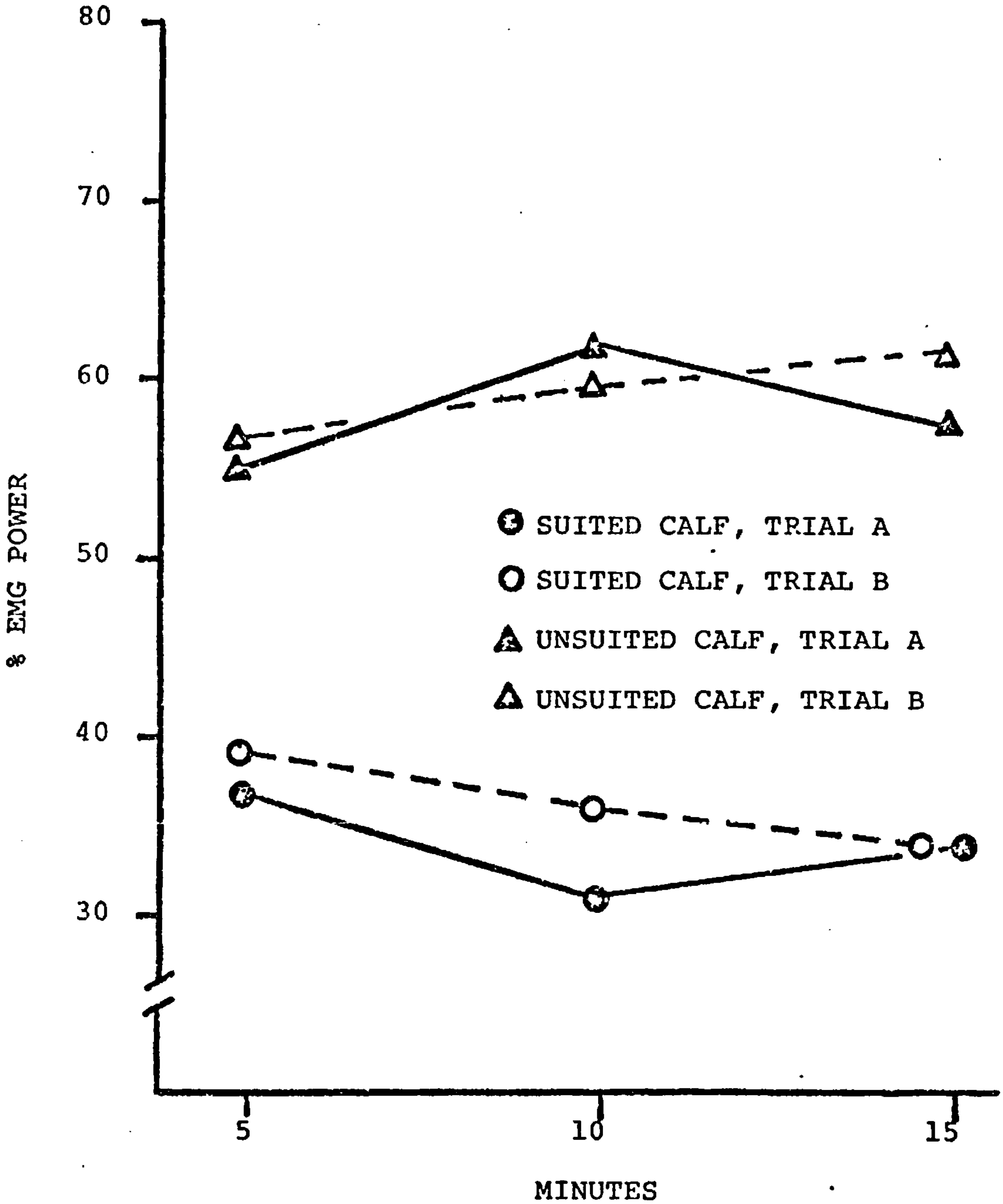


FIGURE 4

PERCENT OF EMG POWER IN 3-30 HZ BAND

FOR THE SUITED AND UNSUITED CALF

WHILE WALKING AT 1 MPH

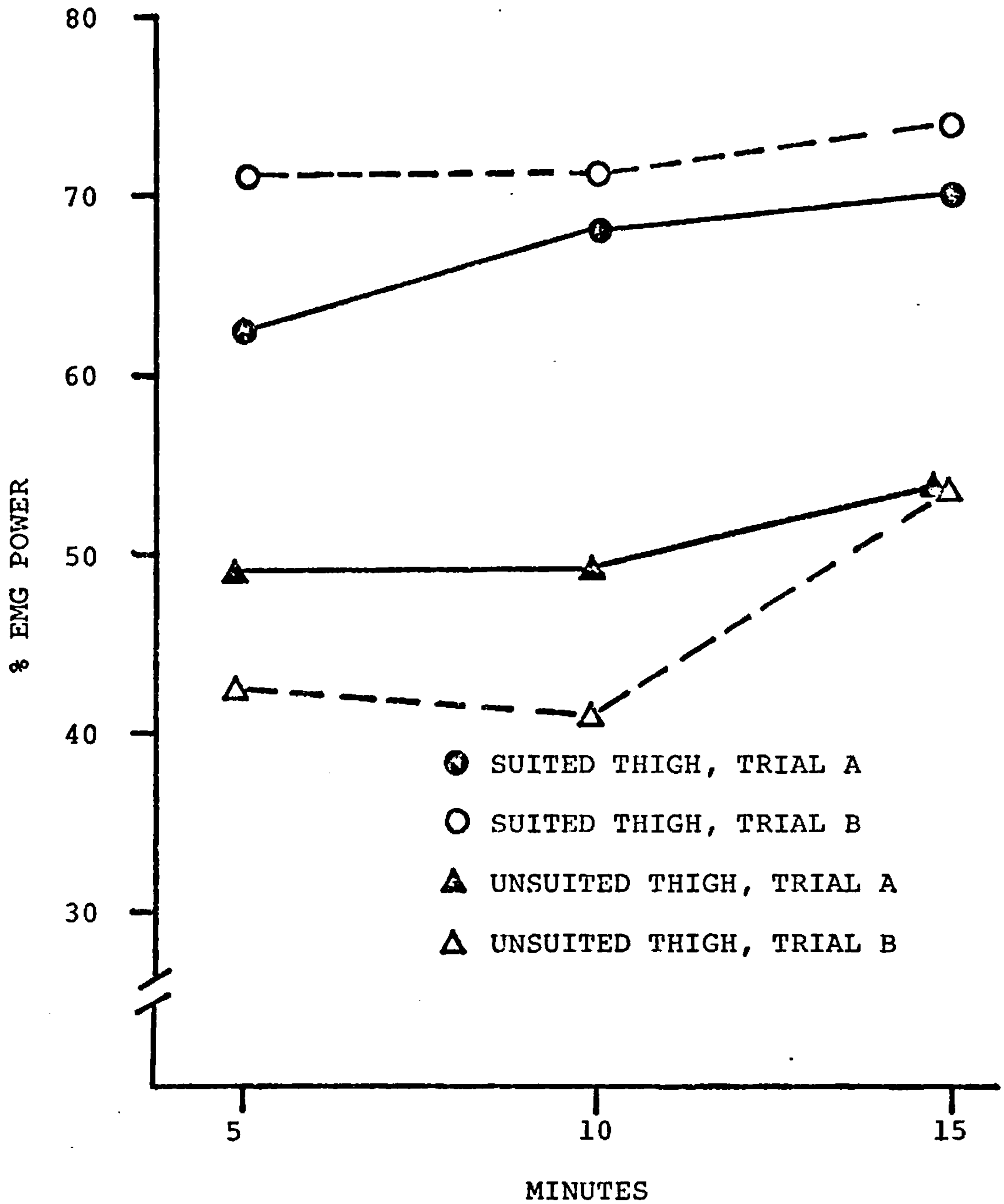


FIGURE 5

PERCENT OF EMG POWER IN 3-30 HZ BAND

FOR THE SUITED AND UNSUITED THIGH

WHILE WALKING AT 2 MPH

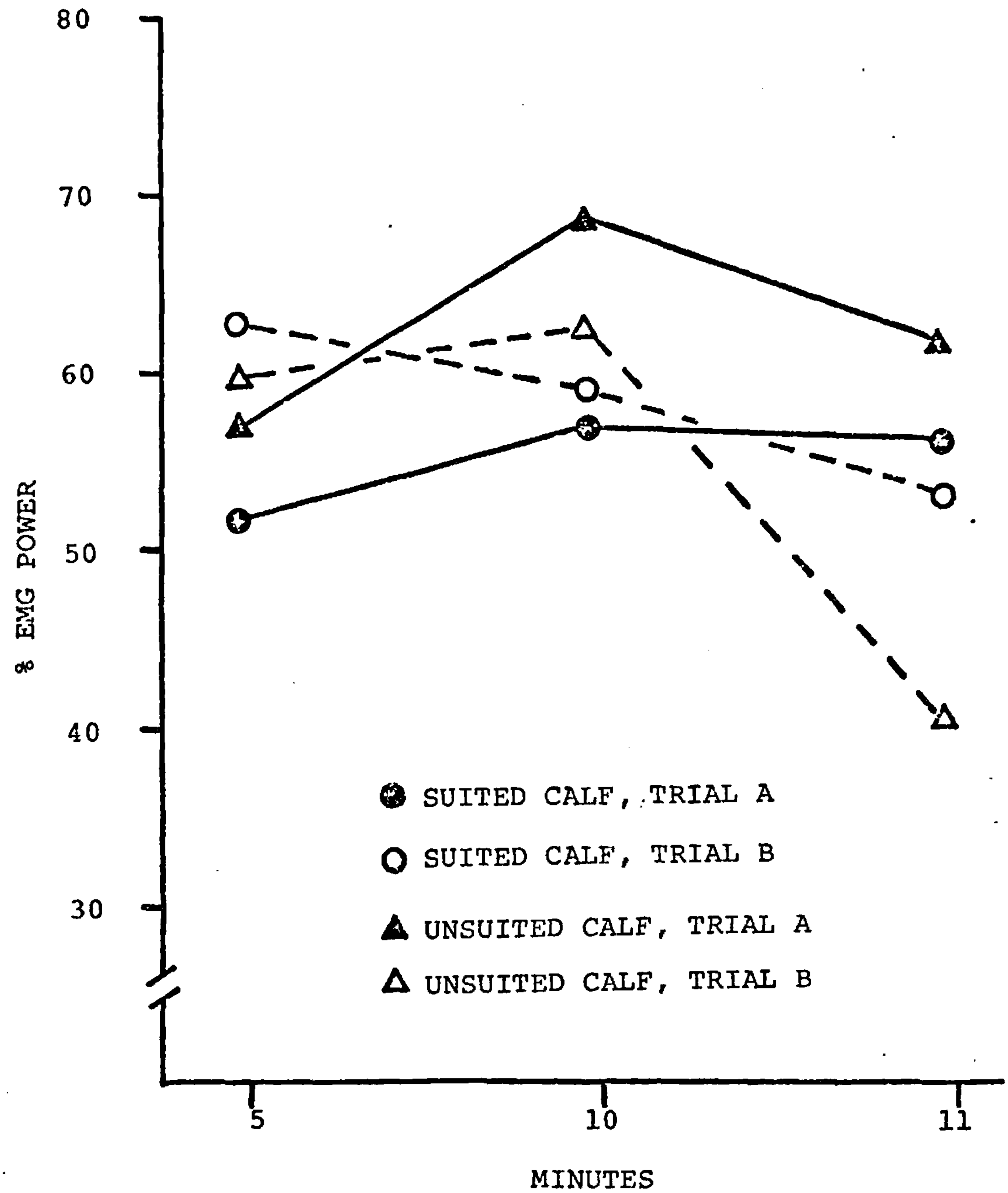


FIGURE 6

PERCENT OF EMG POWER IN 3-30 HZ BAND

FOR THE SUITED AND UNSUITED CALF

WHILE WALKING AT 2 MPH

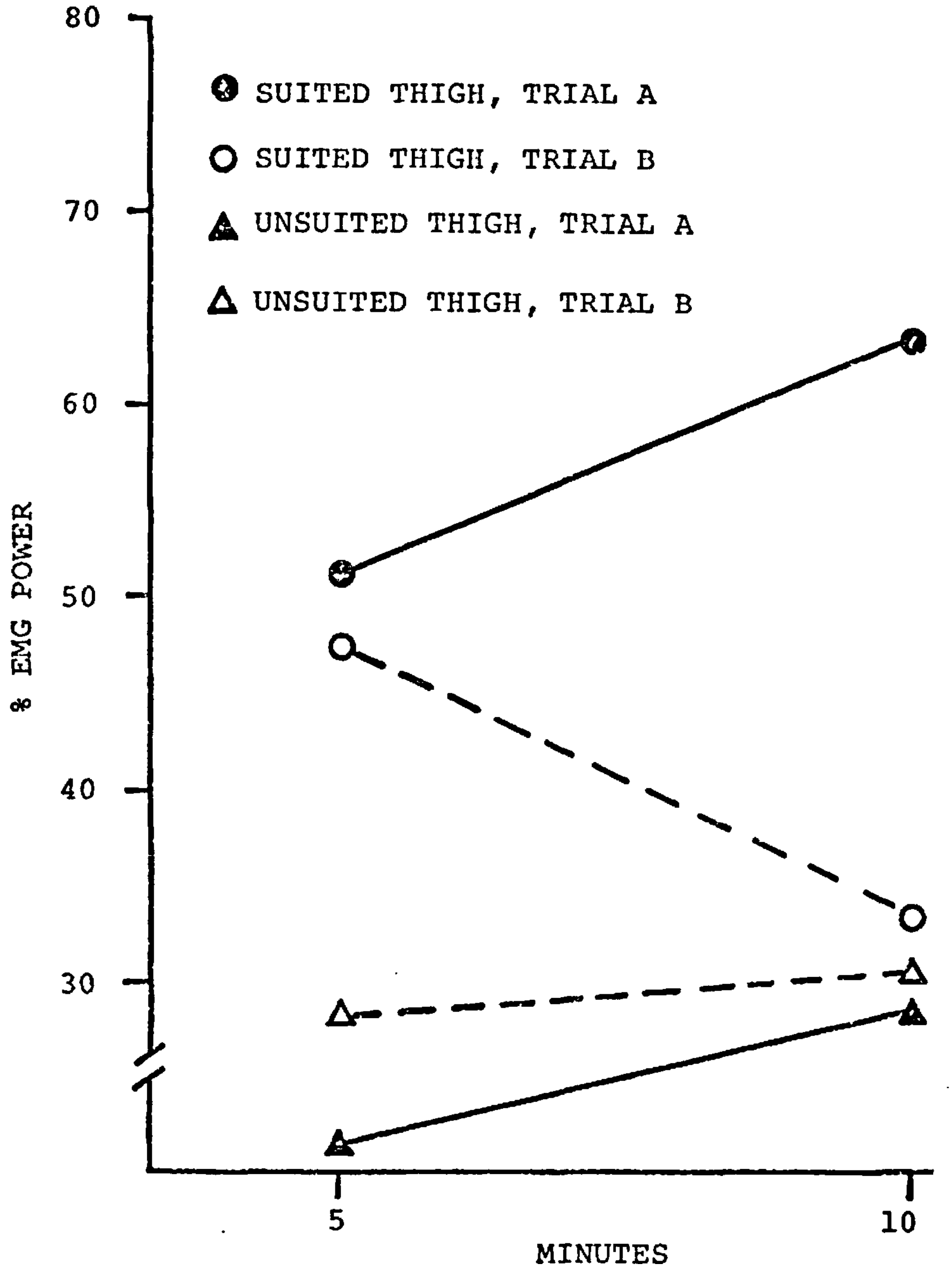


FIGURE 7

PERCENT OF EMG POWER IN 3-30 HZ BAND

FOR THE SUITED AND UNSUITED THIGH

WHILE WALKING AT 3 MPH

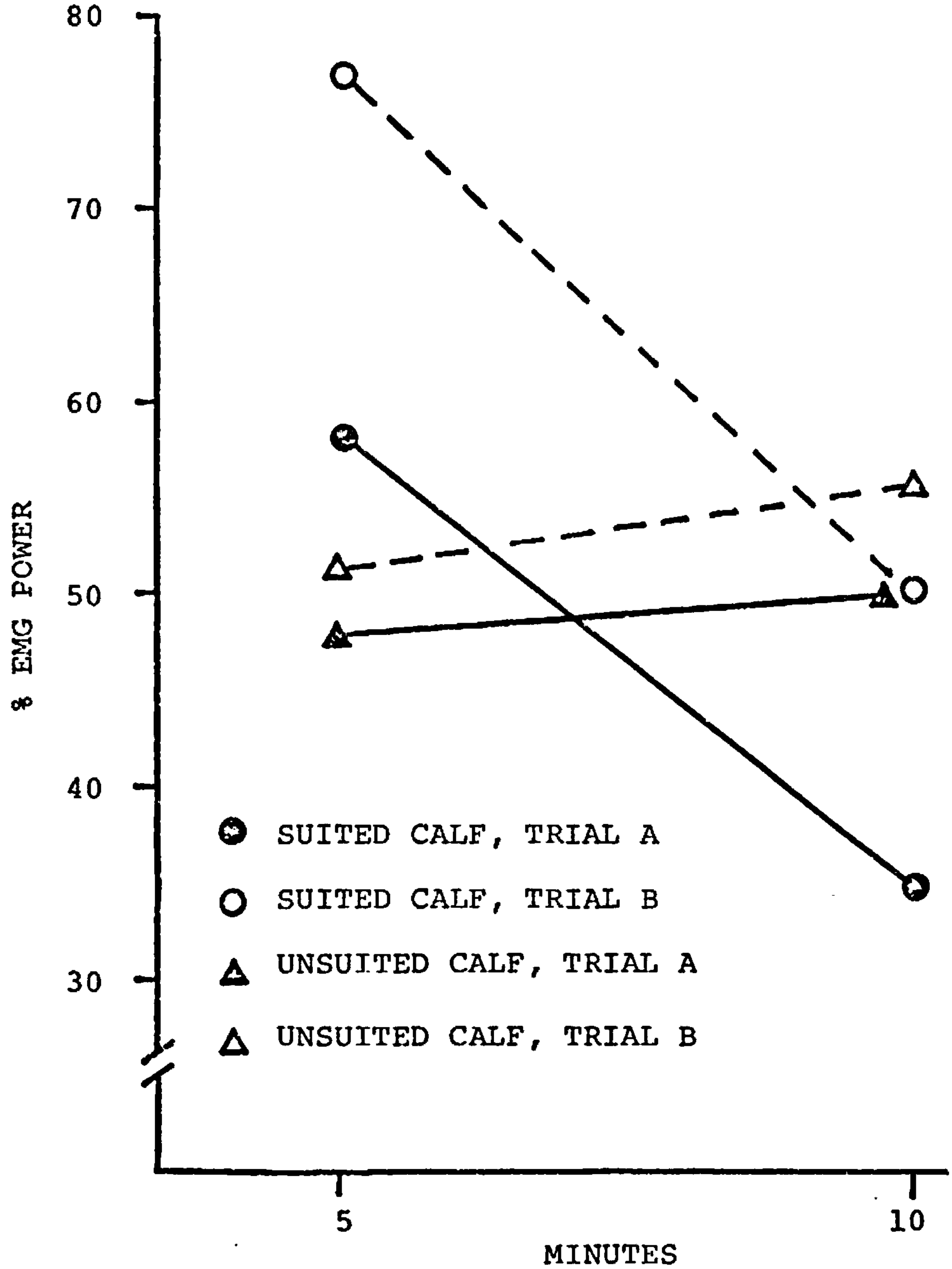


FIGURE 8

PERCENT OF EMG POWER IN 3-30 HZ BAND

FOR THE SUITED AND UNSUITED CALF

WHILE EALKING AT 3 MPH

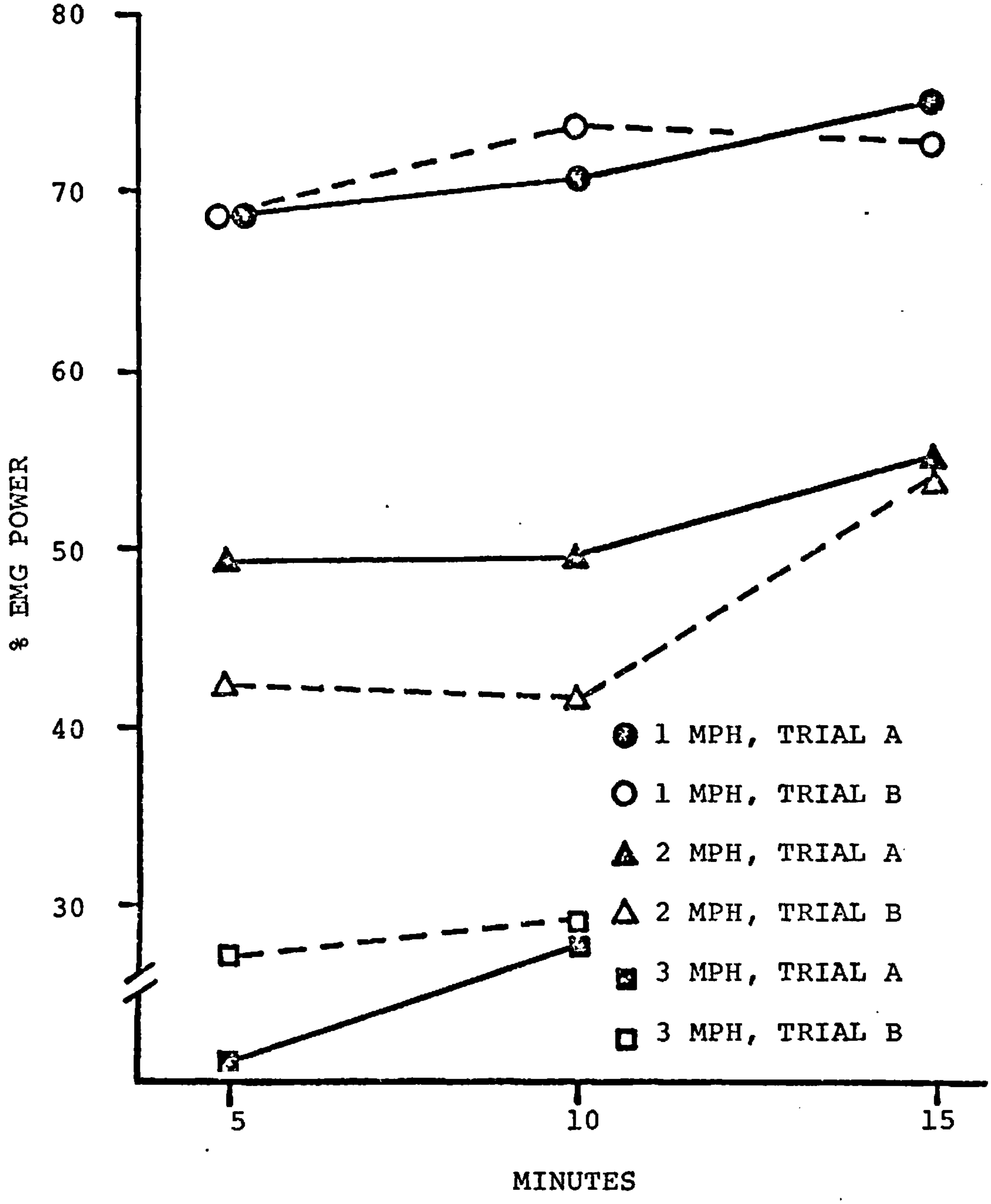


FIGURE 9

PERCENT OF EMG POWER IN 3-30 HZ BAND FOR THE UNSUITED THIGH WHILE WALKING AT 1 MPH, 2 MPH, AND 3 MPH

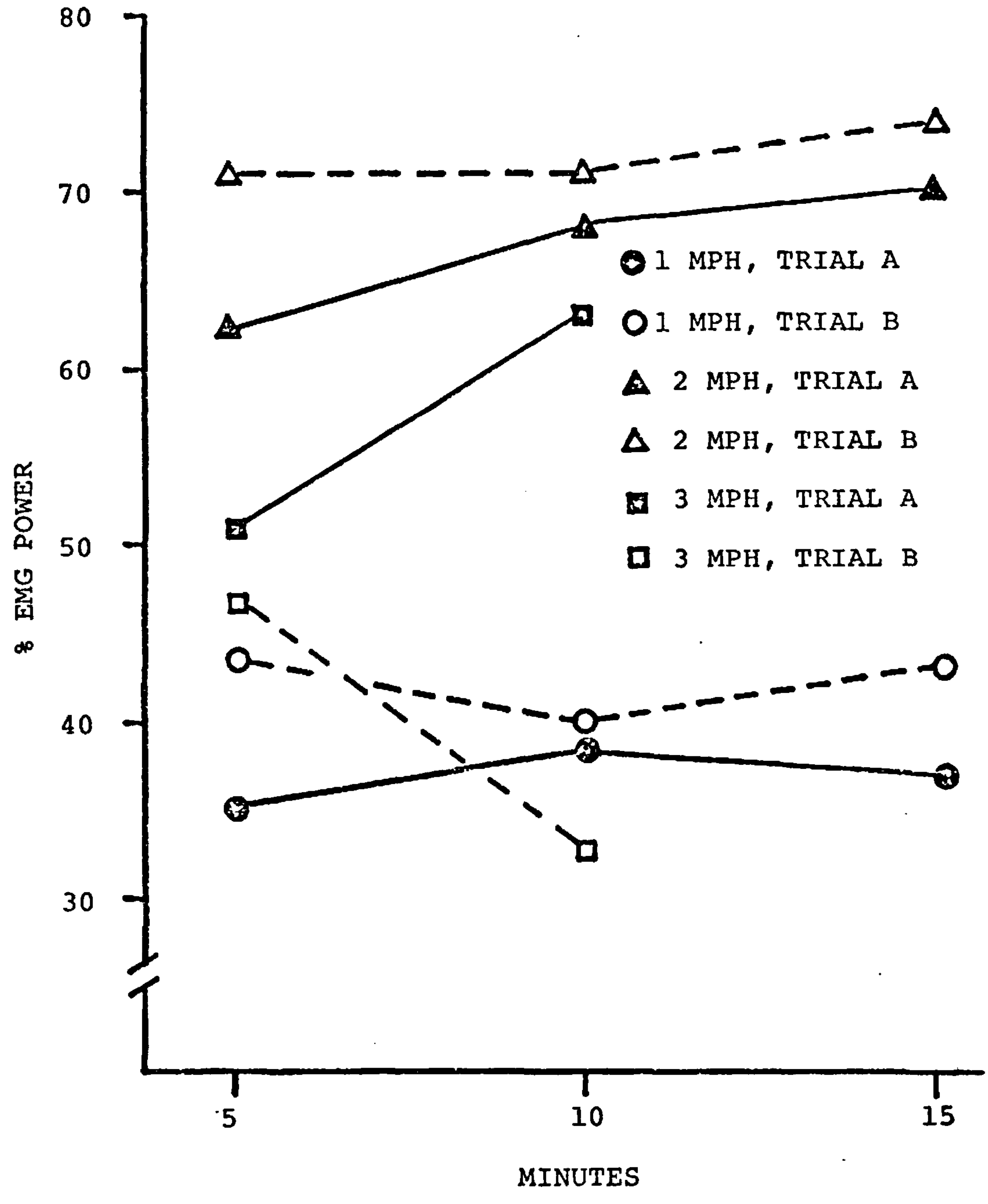


FIGURE 10

PERCENT OF EMG POWER IN 3-30 HZ BAND
FOR THE SUITED THIGH WHILE WALKING
AT 1 MPH, 2 MPH, AND 3 MPH

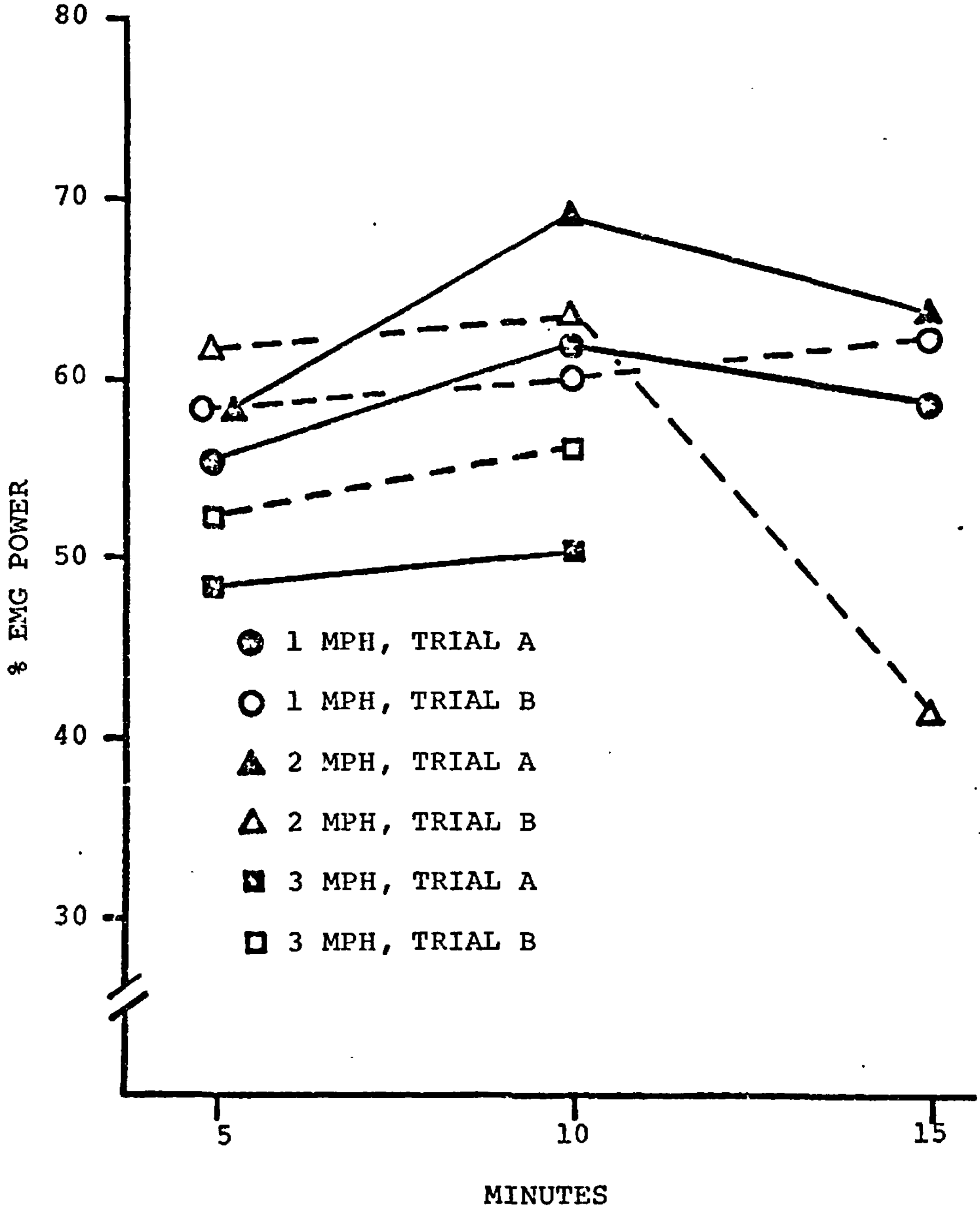


FIGURE 11

PERCENT OF EMG POWER IN 3-30 HZ BAND

FOR THE UNSUITED CALF WHILE WALKING

AT 1 MPH, 2 MPH, AND 3 MPH

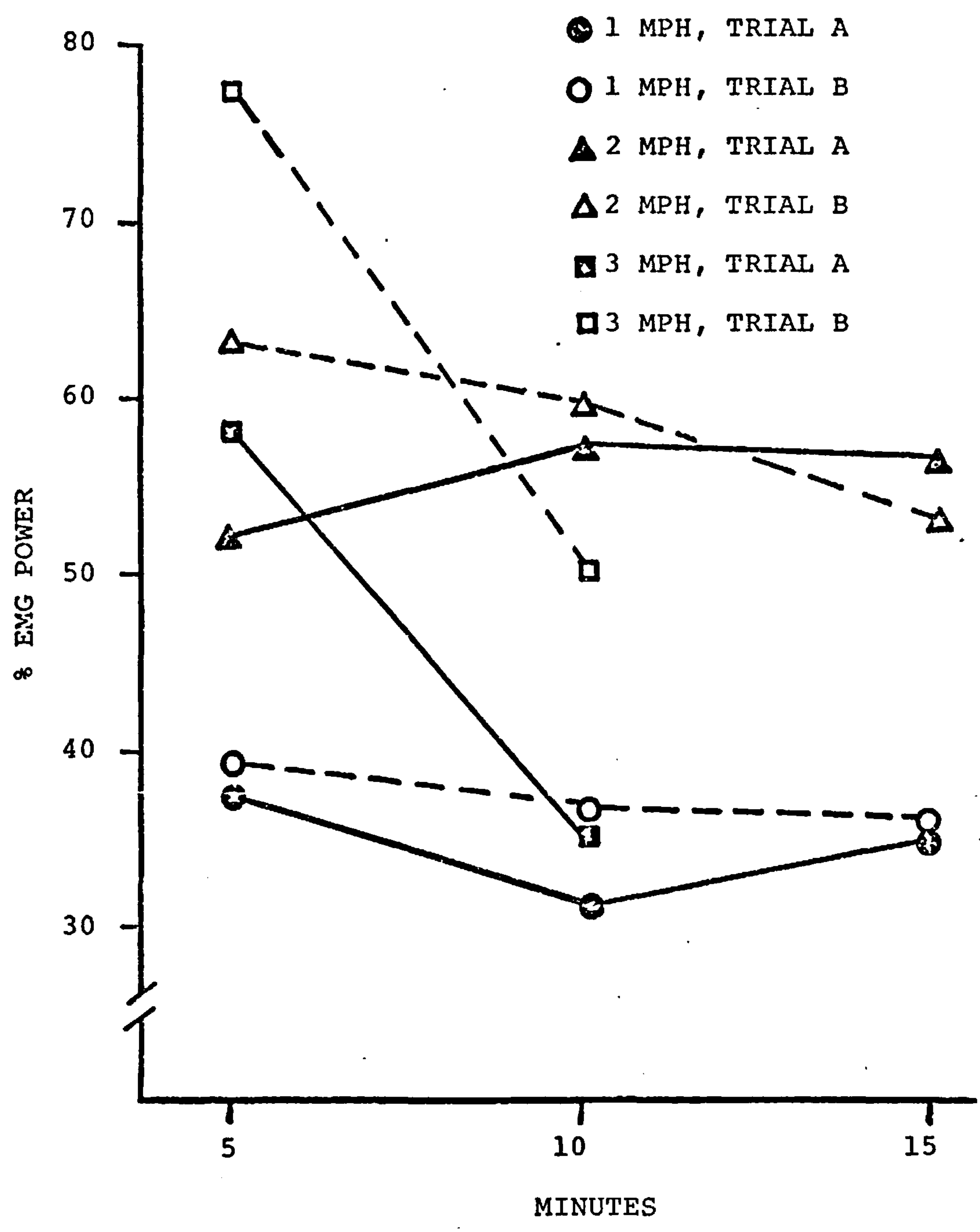


FIGURE 12

PERCENT OF EMG POWER IN 3-30 HZ BAND

FOR THE SUITED CALF WHILE WALKING

AT 1 MPG, 2 MPH, AND 3 MPH

points in time on the abscissa are the 5, 10, and 15 minute measures taken after five, ten, and fifteen minutes of exercise, respectively.

By inspection of the graphs, comparisons can be made between the EMG measures from the calf and thigh for various combinations of the suited and unsuited conditions at the three walking speeds. In addition, the EMG power can be determined for specific combinations of conditions and walking speeds.

Calf and Thigh Compared at Each Speed

From the graphs it can be seen that the pattern of muscle activity for each muscle is markedly different. The thigh (Figures 3, 5, and 7) showed a fairly reliable difference between the suited and unsuited conditions and a similar pattern across time for the A and B trials. The pattern for the calf (Figures 4, 6, and 8) was mixed with a reliable difference between the suited and unsuited conditions at 1 mph, but the differentiation was absent at 2 mph and 3 mph.

A series of Wilcoxon matched-pairs signed-ranks tests (Siegel, 1956) were required to determine the situations in which the calf or thigh muscle groups exhibited an effect. Each EMG percentage from the calf was paired with a comparable EMG percentage from the thigh muscle taken at the same time, e.g., the EMG percentage from the calf taken at 1 mph at the five minute point in the first 15 minute exercise trial was paired with the EMG percentage from the thigh taken at the same speed and point in time. There was a nonsignificant difference between the thigh and calf muscle groups in both the suited or unsuited conditions when combined across the three walking speeds. But, when the suited and unsuited EMG percentages were combined and the three walking speeds analyzed separately, there was a significant difference between the two muscle groups at the walking speeds of 1 mph and 3 mph. At 2 mph the difference between the two muscle groups was significant when the EMG percentages were partitioned according to each condition. Similarly, there was a statistically significant difference between the thigh and calf muscle groups for suited, 1 mph; unsuited, 1 mph; and unsuited, 3 mph; but nonsignificance for the suited, 3 mph combination.

The absence of a significant difference in suited and unsuited conditions and the presence of a difference for the walking speeds indicated that the EMG percentages for the muscle groups were similar in the two conditions and could not be differentiated until the EMG percentages were separated according to walking speeds. Consequently, the muscle groups exhibited a main effect at the three walking speeds but not in the two conditions. The analysis of the muscle groups is summarized in Table 2.

The results of several Wilcoxon matched-pairs signed-ranks tests (Siegel, 1956) for the suited and unsuited con-

TABLE 2

WILCOXON TESTS FOR THE

CALF AND THIGH MUSCLE GROUPS

TESTED COMBINATION	N	T	PROBABILITY
SUITED	18	51.0	NS
UNSUITED	18	78.5	NS
1 MPH	12	1.0	$p < .01$
2 MPH	12	37.0	NS
3 MPH	12	1.5	$p < .05$
1 MPH, SUITED	6	1.0	$p < .05$
1 MPH, UNSUITED	6	0.0	$p < .01$
2 MPH, SUITED	6	0.0	$p < .01$
2 MPH, UNSUITED	6	0.0	$p < .01$
3 MPH, SUITED	6	7.0	NS
3 MPH, UNSUITED	6	0.0	$p < .01$

ditions was similar to the results of the analysis for muscle groups. The combined effect of the conditions for the calf and thigh across the three speeds was not significant. When this effect was separated into its integral components, significant effects started to appear. At all three walking speeds there was a significant difference in EMG percentages for each condition. Furthermore, when the components were separated and reduced to the next level, the significant relationships became more evident, i.e., the suited and unsuited data analyzed at each walking speed. The 2 mph data showed significant differences between the EMG percentages in the suited and unsuited conditions from the thigh an 2 mph, but not the calf at 2 mph. These results are summarized in Table 3.

The Friedman one-way analysis of variance (Siegel, 1956) was used to test the effects of the three walking speeds, i.e., 1 mph, 2 mph, and 3 mph. The three walking speeds did not contribute to significant differences for the calf or thigh, but the differences were significant for the suited and unsuited conditions. Significant differences were revealed when the EMG percentages were separated into individual combinations of the suited and unsuited calf, and suited and unsuited thigh. These results are summarized in Table 4.

At 1 mph, the calf and thigh (Figures 3 and 4) had uniform, differentiated patterns in the unsuited condition. But,

TABLE 3

WILCOXON TESTS FOR THE

SUITED AND UNSUITED CONDITIONS

TESTED COMBINATION	N	T	PROBABILITY
CALF	18	41.0	NS
THIGH	18	79.5	NS
1 MPH	12	0.0	$p < .01$
2 MPH	12	7.0	$p < .01$
3 MPH	12	4.0	$p < .01$
1 MPH, CALF	6	0.0	$p < .01$
1 MPH, THIGH	6	0.0	$p < .01$
2 MPH, CALF	6	7.0	NS
2 MPH, THIGH	6	0.0	$p < .01$
3 MPH, CALF	6	4.0	$p < .05$
3 MPH, THIGH	6	0.0	$p < .01$

TABLE 4

FRIEDMAN ONE-WAY ANALYSIS OF VARIANCE

TESTS FOR THE WALKING SPEEDS

TESTED COMBINATION	DF	χ^2_r	PROBABILITY
CALF	2	3.0	NS
THIGH	2	4.0	NS
SUITED	2	13.0	$p < .01$
UNSUITED	2	13.0	$p < .01$
CALF, SUITED	2	6.0	$p < .05$
CALF, UNSUITED	2	6.0	$p < .05$
THIGH, SUITED	2	8.0	$p < .02$
THIGH, UNSUITED	2	8.0	$p < .02$

at 1 mph in the suited condition, the patterns were not as easily differentiated, although each displayed a different pattern with the thigh muscle group having a higher EMG percentage than the calf muscle group.

At 2 mph (Figures 5 and 6), the conditions were not as easily differentiated as they were at 1 mph. The differences between the calf measures were smaller than similar differences between the thigh percentages because the thigh in the suited condition had the highest percentage of power and the unsuited thigh had the lowest percentage of power with the calf muscle group percentages distributed in between these two extremes. The absence of a pattern in the differences at 2 mph contributed to the statistical nonsignificance of the Wilcoxon test for the calf muscle group in the main effect of conditions at 2 mph. The nonsignificance became statistically significant when the suited and unsuited conditions were tested separately (Table 2).

At 3 mph, the unsuited calf and thigh showed a gradual increase of EMG percentages and a decrease of power for the suited calf. The thigh displayed a different pattern in the suited condition with an increase in EMG power during trial A, which was the opposite of what happened in the calf, and a decrease in power during trial B which was similar to the pattern for the calf. Also, the decrease in power displayed by the suited thigh and calf was not duplicated in any other situation except for the unsuited calf at 2 mph. Another reversal was displayed at 3 mph in which the suited calf had the largest EMG percentage, while at 1 mph the unsuited thigh and calf displayed the largest EMG percentage and at 2 mph the suited thigh displayed the largest EMG percentage.

Calf and Thigh Across Speeds

The unsuited thigh (Figure 9) displayed reliable patterns of increasing EMG power with increased exercise and the three walking speeds were well differentiated into groups of EMG percentages (Table 4). The highest EMG percentage was generated at 1 mph with the second highest level of EMG percentage occurring at 2 mph and the lowest EMG percent at 3 mph. Between the five and ten minute samples there was a gradual increase in the EMG percent at 1 mph, a level trend with no increase between the EMG percentages at 2 mph, and a rather sharp increase in the EMG percentage at 3 mph. The rate of increase in the EMG percentages between the ten minute and 15 minute samples continued to be gradual at 1 mph, but showed an increase at 2 mph. The increase between ten and fifteen minute samples at 2 mph was similar to the increase at 3 mph which occurred between the five and ten minute samples.

The suited thigh (Figure 10) also showed differentiated EMG patterns at each walking speed, but the rate of increase in the EMG percentage was less than the increases at similar speeds for the unsuited thigh (Table 4). At 1 mph there was very little increase in the EMG percentage with continued exercise, at 2 mph the rate of increase was about the same as that observed in the unsuited thigh at 1 mph, but at 3 mph the rapid change in the EMG percentage was rather hard to interpret because there was an increase during trial A and a decrease during trial B. The observed divergence between trial A and trial B did not occur in any other situation. The suited thigh generated the highest EMG percentages at 2 mph, the next highest at 3 mph, and the lowest percentages occurred at 1 mph. This ordering of percentages from high to low was different from the order observed in the unsuited thigh, for in the unsuited thigh the highest percentages occurred at 1 mph instead of 2 mph as they did for the suited thigh and the lowest percentages occurred at 3 mph instead of 1 mph as for the suited thigh.

The unsuited calf (Figure 11) showed a very different pattern of EMG percentages across the suited and unsuited thigh. The differentiated patterns of EMG percentages at each walking speed were absent in the unsuited calf condition (Table 4). Generally, the thigh generated progressively increasing EMG percentages with continued exercise which was what occurred between the five and ten minute measures for the unsuited calf, but the unsuited calf started showing decreases in EMG percentages after ten minutes of exercise. The most rapid decrease occurred at 2 mph during trial B after ten minutes of exercise. Also, gradual decreases occurred during trial A at 1 mph and 2 mph. As in the unsuited thigh condition, the lowest EMG percentages were generated by the unsuited calf at 2 mph. The highest EMG percentages generated by the unsuited calf were at 2 mph, which was similar to the suited thigh, but different than the unsuited thigh.

The pattern of EMG percentages generated by the suited calf (Figure 12) were similar to those observed for the unsuited thigh, but not the unsuited calf. The suited calf displayed differentiated patterns of EMG percentages for each walking speed (Table 4). The decreases in EMG percentages observed at 1 mph and 2 mph in the unsuited calf after ten minutes of exercise were not duplicated in the suited calf. Instead, a drop of EMG percentages occurred at 3 mph after five minutes of exercise. Gradual decreases in EMG percentages occurred at 1 mph and 2 mph after five minutes of exercise. These decreases were not as large as those of the unsuited calf and the decreases occurred after five minutes of exercise instead of after ten minutes of exercise as in the unsuited calf.

In nonparametric procedures, measures of correlation are approximatedby a measure of the relationship, or the extent of association among sets of rankings for a specified number of variables. The Kendall coefficient of concordance (Siegel, 1956) was used to express the degree of association among the three variables speed of walking, muscle group, and conditions. Several combinations of variables were tested in which a specific pattern of statistically significant associations became evident. For all possible combinations of the EMG measures with the speed of walking and suited or unsuited conditions, the significant ($p < .05$) associations resulted for the activity of the calf and thigh muscle. Yet, there were no significant associations between the times of measurement, regardless of how the walking speed and condition variables were combined for each test of association. The significant associations between muscle groups and absence of any association between points in time of sampling can best be interpreted to mean that the calf and thigh muscle activity during the exercise is correlated for each situation, i.e., a general overall trend toward increased EMG percentages, but this trend is not the same for each muscle at any one point in time. If a shared trend does exist, it seems incongruent for them to differ at selected times, but apparently the associated muscle activity varies enough to create minute-to-minute differences in the thigh and calf EMG percentages.

In summary, the graphic presentations display the individual action of the thigh and calf muscle groups. The graphic presentations demonstrate, as do the Wilcoxon tests, that the individual activity of each muscle group is very dependent on the walking speed and whether that walking speed was accomplished in the suited or unsuited condition. Statistically, and graphically, the muscle activity, as measured by EMG percentages, can be easily differentiated into the suited and unsuited condition at 1 mph, but not so easily differentiated at 3 mph, and cannot be differentiated at 2 mph. The EMG percentages differentiated the activity of the muscle groups at each walking speed for the suited calf and thigh muscle groups and the unsuited thigh, but the results for the unsuited calf muscle group are not as obvious. The results for the unsuited calf at each walking speed are mixed, i.e., not easily differentiated into walking speeds. There is not a definite pattern of the highest and lowest EMG percentages at the different walking speeds, i.e., neither the calf nor the thigh muscle groups consistently generated the highest EMG percentages across the three walking speeds and/or the suited and unsuited conditions. Although this might be perplexing statistically, it is beneficial for isolating muscle group activity because the patterns of EMG percentages are somewhat unique for extended periods of exercise.

Muscle Fatigue

Originally, the proposed operational definition outlined in the Method section of Chapter III emphasized that when muscle fatigue occurred there was a corresponding shift in EMG power, i.e., an increase of EMG percentages in a low, broad frequency band. Although the frequency analysis technique did prove feasible for differentiating muscle activity in terms of EMG percentages, the EMG percentage data collected in this research did not give any information about muscle fatigue because the original operational definition of muscle fatigue was not appropriate, i.e., the EMG percentages increased and decreased. Consequently, a discussion of local muscle fatigue at the three walking speeds and in the two conditions will have to wait for the development of an alternative operational definition of muscle fatigue that is compatible with the EMG data collected in this research. Such an alternative definition is presented in the Discussion, Chapter V.

CHAPTER V

DISCUSSION

As predicted, the frequency analysis revealed different EMG signals from the calf and thigh muscle groups in the suited and unsuited conditions at each walking speed. The EMG signals had a different frequency analysis pattern for each selected muscle group and the statistical analyses for muscle groups showed a significant difference between the two muscle groups at 1 mph and 3 mph in each condition with significance at 2 mph when the data was partitioned according to conditions. Thus, the two muscle groups were primarily effected by the three walking speeds, and secondarily by the two conditions (Table 2).

Hypothesis one was partially supported because the EMG signals from loaded muscles (suited condition) had a different frequency analysis pattern than EMG signals from unloaded muscles (unsuited condition), but neither condition consistently produced the most EMG power. Although the effect of the two conditions was not significant for the combined calf and thigh data, there were significant differences for each muscle group at all three walking speeds (Tables 3 and 4). The difference was presented graphically in Figures 3-8. In these figures there was a definite separation of the suited and unsuited data points, except for the calf at 2 mph (Figure 6).

The EMG signals did, as predicted in hypothesis two, have a different frequency analysis pattern for each level of task difficulty, but, no single walking speed consistently produced the highest level of EMG power. The combined calf and thigh data did not result in significant differences between the walking speeds for the suited and unsuited calf and the suited and unsuited thigh (Table 4).

Partial support for hypothesis three was found because the EMG signals did have different frequency analysis patterns at selected points in time during the exercise period, but, the EMG power did not continuously increase with progressively longer exercise periods. Instead, there were increases and decreases of EMG power with extended exercise.

There are basically four unique aspects to this research. First, the use of frequency analysis to help interpret the EMG signals, second the use of frequency analysis on EMG signals from muscles active in isotonic exercise, thirdly, the operational characteristics of the testing situation, and finally the time-series sampling, or elapsed time samples. One subset of Chaffin's (1969a) data, and this research effort, are the only known experimental designs on muscle fatigue that use time-series sampling of the EMG signal. The advantage of the time-series sampling is that the rate of fatigue can be monitored.

Chaffin (1969a) had his subjects hold weights which were attached to a padded wrist cuff. The object was to suspend the weights with the forearm in a horizontal position for as long as possible while the EMG was recorded from the biceps brachii. The rate of fatigue, as indicated by the slopes of fitted lines, increased with each successively heavier weight. The five pound weight was held for about 36 minutes, while the 25 pound weight was held for less than three minutes. For each weight the slopes of the fitted lines were always positive.

The results of the current research are at variance with Chaffin's (1969a) operational definition of muscle fatigue which was used to pattern the operational definition given in the Method section of Chapter III in this research report, and his data which shows a constant increase of EMG power in the low, broad frequency band as the muscle is exercised to a point of fatigue.

Specifically, the operational definition describes the onset of fatigue at that point where, during a prescribed work task, the frequency analysis shows an increase in the EMG power in a low, broad frequency band. But, as reported in the results section, the EMG power, as indicated by EMG percentages, not only increases, but also decreases. The decreases in EMG percentages cannot be interpreted with Chaffin's operational definition. Similarly, Chaffin (1969a) reported that the EMG power in the low, broad frequency band always increased, i.e., never showed a decrease, not even just before the test weights were dropped which indicated that the subjects could no longer support the test weight. This constant increase in EMG power leads to untenable predictions which require an ever increasing, unlimited source of myo-potentials. It is difficult to find physiological evidency to support these predictions. Since the EMG signal capturing technique and equipment, low frequency band, and frequency analysis techniques used in this research were comparable to Chaffin's, the most likely cause of the disparity is the type of exercise involved. Chaffin used an isometric exercise while an isotonic exercise was used for this research.

Consequently, when the prescribed task used to generate myo-potentials and to develop muscle fatigue is an isotonic exercise instead of an isometric exercise some adjustments should be made in the operational definition of muscle fatigue and the expected EMG power trends during and after the onset of muscle fatigue.

An obvious question to ask is what happens to the EMG after the muscle fatigues? The percent of power should reach a maximum at which point the curve will either flatten out or decrease, it cannot always increase as would be the case if Chaffin's (1969a) results were extended to their extreme. Such a decrease in the EMG power was observed in this research. A visual inspection of Figures 3-12 reveals that there are increases and decreases in EMG percentages.

The increases and decreases in EMG percentages do follow a pattern, the interpretation of which extends the applicability and operational feasibility of using the frequency analysis to analyze EMG signals for muscle fatigue. Previous studies have established the increase in EMG percentages prior to the onset of fatigue but there have been no descriptions of what the EMG percentages do after fatigue. According to the results of this study, the EMG percentages decrease after fatigue. One interpretation of these increases and decreases could be that the muscle fatigues at the point where the positively accelerated curve changes to a negative acceleration. But the data collected in this research does not support that interpretation because the curve which represents the plotted EMG percentages changes directions several times during each 15 minute trial.

An alternate interpretation could be that the muscle fatigues at the point in time when the largest EMG percentage is recorded. The data from this research tends to support the interpretation that the largest EMG percentage represents the onset of fatigue. For example, in Figure 3 the largest percentage at 1 mph for the unsuited thigh occurred at 15 minutes into trial A, and at ten minutes into trial B. Similarly, for the suited thigh at 1 mph, the largest EMG percentage occurred at ten minutes into trial A, and at five minutes into trial B. These results are logical enough to lend validity to the use of the largest EMG percentage as a criteria for muscle fatigue, i.e., they are logically predictable and the relative relationships are not generally inconsistent or contradictory.

This focus on the largest EMG percentage to indicate muscle fatigue is not an attempt to degrade previous research results or operational definitions of muscle fatigue, but an attempt to develop an alternative operational definition that is applicable to EMG data collected from muscles active in isotonic exercise. Previous operational definitions of muscle fatigue had two components, viz., an increase in EMG power, and that the increase occurred in a low, broad frequency band. A focus on the largest EMG percentage in the low, broad band uses the increase component and the low, broad band component of the original operational definitions plus adding a third component, i.e., the largest EMG percentage. Such an alternative operational definition of muscle fatigue would be that: During a prescribed work task which involves isotonic exercise, the onset of muscle fatigue coincides with the largest EMG percentage (EMG power) that occurs in a low, broad frequency band.

Several relationships between the independent variables can be isolated by using an operational definition that focuses on the largest EMG percentage as a criteria of muscle fatigue. Inspection of Figure 13 shows that the thigh muscle group and the calf muscle group fatigue at different rates, i.e., points in time; with the calf muscle group fatiguing before the thigh muscle group. This is consistent

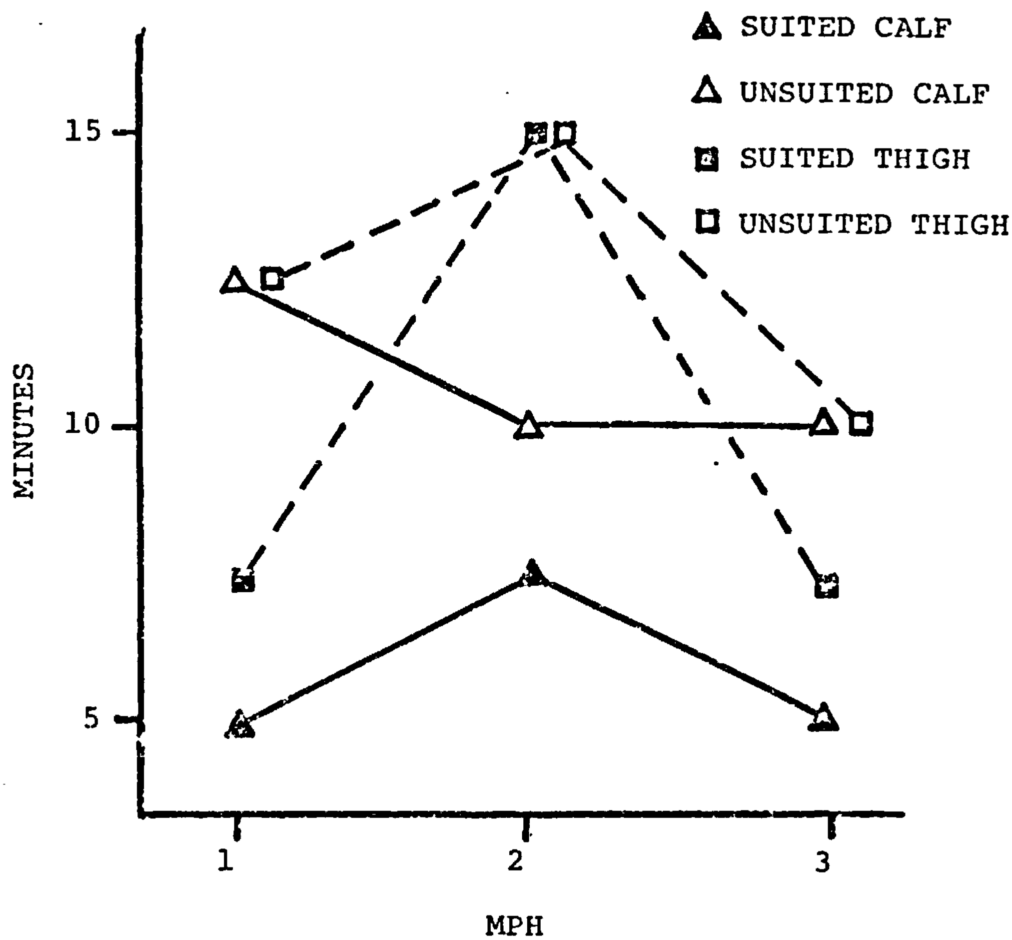


FIGURE 13

TIME AT WHICH LARGEST EMG PERCENTAGE OCCURS FOR THE CALF AND THIGH MUSCLE GROUPS AT EACH WALKING SPEED with research results on the human walking cycle. Traditionally, the human gait is described as two phases: (1) stance, beginning when the heel strikes the ground, and (2) swing, beginning with toeing-off. Radcliffe (1962) used EMG records to illustrate the phasic interaction of major muscle groups in the walking cycle. He reported that as the heel strikes the ground the thigh muscle group increases in activity as the torso is carried forward over the limb, apparently to maintain knee stability. Then, at heel-off the calf group of muscles build to a peak of activity that ceases with toe-off. During the walking cycle the thigh muscle group is active about 30 percent of the time, while the calf muscle group is active approximately 50 percent of the time. Also, Eberhart, Inman, and Bresler (1954) report that the primary function of the calf muscle group during walking is to push-off, i.e., they lift the body against gravity on the forepart of the foot. Consequently, it is not difficult to see why the calf muscle group fatigued before the thigh muscle group, particularly in the suited condition.

Another relationship revealed with the largest EMG percentage as a criteria for the onset of muscle fatigue, which is also graphically illustrated in Figure 13, was that both muscle groups fatigued in the suited condition before they did in the unsuited condition. This difference between the conditions is more clear cut for the calf muscle group than the thigh muscle group. Which, again, highlights the complexity cf the relationships between the two muscle groups.

The largest EMG percentages can be used to show the different rates of fatigue at each walking speed. Again referring to Figure 13, at 1 mph the onset of fatigue, i.e., the largest EMG percentage, occurred at approximately 12 minutes for both the unsuited calf and thigh, but at seven minutes and five minutes for the suited thigh and calf, respectively. At 2 mph the suited and unsuited thigh fatigued at 15 minutes, and the suited calf at approximately seven minutes. Then, at 3 mph the unsuited calf and thigh fatigued at ten minutes, the suited thigh at seven minutes and the suited calf at five minutes.

From a different perspective, fatigue occurred after about seven minutes of exercise for the suited thigh at 1 mph, the suited calf at 2 mph, and the suited thigh at 3 mph. There was no difference in the time of fatigue for the unsuited calf at 2 mph, or the unsuited calf and unsuited thigh at 3 mph. The unsuited calf and thigh fatigued after approximately 12 minutes at 1 mph and the suited and unsuited thigh at 2 mph.

These rates of fatigue indicate that generally the onset of fatigue occurred earlier at 1 mph and 3 mph than at 2 mph. At first this result may appear contradictory, but all the subjects agreed that walking at 2 mph was the most comfortable, or natural pace, while walking at 1 mph was unnatural and awkward, and walking at 3 mph was truly "fatiguing".

Future research on local muscle fatigue should use the frequency analysis technique to investigate two parallel paths. The first would be to further develop the exploratory/baseline muscle fatigue data from this research with more elaborate research designs which include frequent time-series sampling to further detail the onset of muscle fatigue and delineate levels of muscle fatigue. The second, and parallel, research effort should attempt to find the behavioral correlates that accompany various levels of muscle fatigue in the hope of providing useful information to industrial designers that will help them predict the onset of muscle fatigue and, in turn, offer suggestions for delaying muscle fatigue, reducing work errors, and increasing productivity with appropriately designed work areas/tasks.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The purpose of this research was twofold; first the purpose was to use the technique of frequency analysis to interpret EMG signals generated in an operational situation which involved isotonic exercise to develop baseline indexes of local muscle fatigue and, second, to fill descriptive gaps about changes in the EMG signal as selected muscle groups were exercised to develop fatigue. A unique combination of exercise, electrodes, muscle groups, and analysis were used to capture EMG signals from the thigh and calf muscle groups with surface electrodes while each of four subjects walked with and without a full pressure suit at 1 mph, 2 mph, and 3 mph. The purpose of the full pressure suit was to load the selected muscle groups and to provide muscle fatigue data from loaded muscles for comparisons with muscle fatigue data from unloaded muscles. The captured EMG signals from the selected muscle groups was recorded and analyzed with the frequency analysis technique to provide the percentage of EMG power in a low, broad frequency band (3-30 Hz).

Results of the non-parametric statistical analyses and graphic comparisons showed the individual activity of the muscle groups and the interdependent relationships between the effect of walking speed and suited or unsuited conditions on each muscle group. These relationships were interpreted from the patterns of EMG percentages in the time-series samples taken at five-minute intervals during each 15-minute exercise trial. For each muscle group, the EMG percentages showed a difference between the three walking speeds (Table 2, Figures 9-12), but within each muscle group there was no difference between the suited and unsuited conditions (Table 2, Figures 3-8). For each condition, the EMG percentages showed a difference between the three walking speeds (Table 3, Figures 9-12), but within each condition, there was no difference between the thigh and calf muscle groups (Table 3, Figures 3-8). At the individual walking speeds the EMG percentages showed a difference between the suited and unsuited conditions (Table 4, Figures 9-12), but within each walking speed there was no difference between the calf and thigh muscle groups (Table 4, Figures 9-12). Therefore, the individualized activity of each muscle group is dependent on the walking speed and whether the walking speed was accomplished in the suited or unsuited condition. The muscle activity as measured by EMG percentages, can be easily differentiated into suited and unsuited conditions at 1 mph, less easily at 3 mph, and cannot be differentiated at 2 mph. The EMG percentages differentiated the activity of the muscle groups at each walking speed for the suited calf and thigh muscle groups and the unsuited thigh, but the results for the unsuited calf muscle group were not as obvious. The results for the unsuited calf at each walking speed were mixed, i.e., the different walking speeds were not distinguished by different patterns of the highest and lowest EMG percentages. There was not a definite pattern of the highest and lowest EMG percentages at the different walking speeds, i.e., neither the calf nor thigh muscle groups consistently generated the highest EMG percentages across the three walking speeds and/or the suited or unsuited conditions.

Originally, the proposed operational definition outlined in the Method section of Chapter III emphsized that when muscle fatigue occurred there was a corresponding shift in EMG power, i.e., an increase of EMG percentages in a low, broad frequency band. But, the original operational definition could not be used with the data collected in this research because the EMG percentages increased and decreased. Consequently, an alternative operational definition of muscle fatigue was proposed for EMG percentages developed during isotonic exercise, viz., that in a prescribed work task using isotonic exercise, the onset of fatigue coincides with the largest EMG percentage (EMG power) that occurs in a low, broad frequency band. By using the largest EMG percentage as a criteria for muscle fatigue, relationships evolved between the independent variables to give an indication of muscle fatigue which, for the EMG data collected in this research, was not available with the original operational definition. The largest EMG percentage showed that the thigh and calf muscle groups fatigued at different rates with the calf muscle groups fatiguing in the suited condition before the thigh muscle group (Figure 13). Also, both muscle groups fatigued in the suited condition before they did in the unsuited condition. The largest EMG percentage showed different rates, or times, at which muscle fatigue occurred for each walking speed, e.g., at 1 mph fatigue occurred after approximately 12 minutes of exercise for both the unsuited calf and thigh, but after seven minutes and five minutes for the suited thigh and calf, respectively. At 2 mph, the suited and unsuited thigh fatigued after 15 minutes of exercise, the suited thigh after ten minutes, and the suited calf after approximately seven minutes of exercise. Then, at 3 mph, the unsuited calf and thigh fatigued after ten minutes of exercise, the suited thigh after seven minutes, and the suited calf after five minutes of exercise.

From a different perspective, fatigue occurred after about seven minutes of exercise for the suited thigh at 1 mph, the suited calf at 2 mph, and the suited thigh at 3 mph. There was no difference in the time of fatigue for the unsuited calf at 2 mph, or the unsuited calf and unsuited thigh at 3 mph. The unsuited calf and thigh fatigued after approximately 12 minutes at 1 mph and the suited and unsuited thigh at 2 mph (Figure 13).

These rates of fatigue indicate that, generally, the onset of fatigue occurred earlier at 1 mph and 3 mph than at 2 mph. At first this result may appear contradictory, but all the subjects agreed that walking at 2 mph was the most comfortable, or natural pace, while walking at 1 mph was unnatural and awkward, and walking at 3 mph was truly "fatiguing".

Based on the results of this research several general and specific conclusions can be drawn. The specific conclusions, which are limited to the focus of this research, include:

(1) The calf and thigh muscle groups have individual and shared characteristics such that both muscle groups exhibited different patterns of EMG percentages in the unsuited condition and the shirtsleeve (unsuited) condition, but within each condition each muscle group exhibited a different EMG pattern.

(2) The thigh muscle, while in the suited condition, fatigued at the walking speeds of 1 mph and 3 mph before it fatigued at 2 mph.

(3) The thigh muscle, while in the shirtsleeve (unsuited) condition, fatigued sooner at the walking speed of 3 mph than it fatigued at 1 mph which was, in both cases, before it fatigued at 2 mph.

(4) The calf muscle, while in the suited condition, fatigued at the walking speeds of 1 mph and 3 mph before it fatigued at 2 mph.

(5) The calf muscle, while in the shirtsleeve (unsuited) condition, fatigued at the walking speeds of 2 mph and 3 mph before it fatigued at 1 mph.

(6) Generally, the walking speeds of 1 mph and 3 mph were more fatiguing for the thigh and calf muscle groups, regardless of muscle loading.

General conclusions which can be developed from the results of this research are:

(1) The frequency analysis technique is an operationally feasible, and valuable, tool for interpreting the complex interference pattern of the electromyogram from muscles involved in isotonic exercise for the purpose of describing the onset of local muscle fatigue, and detailing rates of local muscle fatigue.

(2) Future research using the frequency analysis technique should investigate two parallel paths. The first would be to further develop the exploratory/baseline muscle fatigue data from this research with more elaborate research designs which include frequent time-series sampling to further detail the onset of muscle fatigue and delineate levels of muscle fatigue. The second, and parallel,

research effort should attempt to find the behavioral correlates that accompany various levels of muscle fatigue in the hope of providing useful information to industrial designers that will help them predict the onset of muscle fatigue and, in turn, offer suggestions for delaying muscle fatigue, reducing work errors, and increasing productivity with appropriately designed work areas/tasks.

BIBLIOGRAPHY

BIBLIOGRAPHY

Bartley, S. H. The human organism as a person. New York: Chilton Book Co., 1967.

Bartley, S. H. and Chute, Eloise. Fatigue and impairment in man. New York: McGraw-Hill Co., 1947.

Basmajian, J. V. Muscles alive, their functions revealed by electromyography, second edition. Baltimore: The Williams and Wilkins Co., 1967.

Basmajian, J. V. Electromyography comes of Age. Science. 1972, 176, 603-609.

Chaffin, D. B. Surface electromyography frequency analysis as a diagnostic tool. Journal of Occupational Medicine, 1969, 11, 109-115. (a)

Chaffin, D. B. Electromyography-a method of measuring local muscle fatigue. Journal of Methods-Time Measurement, 1969, 14, 29-36. (b)

Close, J. R., Nickel, E. D., and Todd, A. B. Motor unit action potential counts--their significance in isometric and isotonic contractions. Journal of Bone and Joint Surgery, 1960, 7(October, 42-A), 1207-1222.

Currier, D. P. Measurement of muscle fatigue. Physical Therapy, 1970, 49(7), 724-730.

deVries, H. A. Efficiency of electrical activity as a physiological measure of the functional state of muscle tissue. American Journal of Physical Medicine, 1968, 47, 10-22.

deVries, H. A. Muscle forms in postural muscles. American Journal of Physical Medicine, 1965, 44, 275-291.

Eberhart, H. D., Inman, V. T., and Bresler, B. The principle elements of human locomotion. In Basmajian, J. V. Muscles alive. Baltimore: The Williams and Wilkins Co., 1967.

Edwards, G. R., and Lippold, O. C. J. The relation between force and integrated electric activity in fatigued muscle. Journal of Physiology, 1956, 132, 677-681.

Gregg, L. W., and Jarrard, L. E. Changes in muscle action potentials during prolonged work. Journal of Comparative and Physiological Psychology, 1958, 51, 532-535.

Hashimoto, K., Kogi, K., and Grandjean, E. (eds.) Methodology in human fatigue assessment. London: Taylor & Francis Ltd., 1971.

Hayes, K. J. Wave analyses of tissue noise and muscle action potentials. Journal of Applied Physiology, 1960, 15, 749-752.

Inman, V. T., Ralston, H. J., Saunders, J. B., Feinstein, B., and Wright, Jr., E. W. Relation of human electromyogram to muscular tension. EEG and Clinical Neurophysiology, 1952, 4, 187-194.

Kadefors, R., Kaiser, E., and Petersen, I. Methods for studying the modifications in frequency spectrum of myo-potentials at slow and fast muscle contractions. Journal of Electroencephalography and Clinical Neurophysiology, 1968, 24, 89.

Kaiser, E., and Petersen, I. Frequency analysis of muscle action potentials during tetanic contraction. Electromyography, 1963, 3, 5-17.

Kaiser, E. and Petersen, I. Muscle action potentials studied by frequency analysis and duration measurement. Acta Neurol. Scandinav, 1965, 41, 19-41 in Basmajian, J. V. Muscles Alive. Baltimore: The Williams and Wilkins Co., 1967.

Kogi, K., and Hakamade, T. Slowing of surface electromyogram and muscle fatigue. Republic Institute Science Laboratory, 1962, 60, 27-41 in Linstrum, L., Magnussan, R., and Petersen, I. Muscular fatigue and action potentials conduction velocity changes studied with frequency analysis of EMG signals. Electromyography, 1970, 4, 341-355.

Lindquist, C. The motor unit potential in severely paretic muscles after acute anterior poliomelitis: and electromyographic study using fatigue experiments. Acta psychiat. et neurol. Scandinav., 1959, 34, 1-72 in Basmajian, J. V. Muscles Alive. Baltimore: The Williams and Wilkins Co., 1967.

Lippold, O. C. J., Redfearn, J. W. T. and Vuco, J. The electromyography of fatigue. Ergonomics, 1960, 3, 121-132.

Merton, P. A. Voluntary strength and fatigue. Journal of Physiology, 1954, 123, 553-564.

Missiuro, W., Kirschner, H., and Kozolowski, S. Electromyographic manifestations of fatigue during work of different intensity. Acta physiol polon, 13, 11-13 in Basmajian, J. V. Muscles Alive. Baltimore: The Williams and Wilkins Co., 1967.

Radcliffe, C. W. The biomechanics of below-knee prostheses in normal level bipedal walking. Artificial Limbs, 1962, 6, 16-24 in Basmajian, J. V. Muscles Alive. Baltimore: The Williams and Wilkins Co., 1967.

Ralston, H. J. Uses and limitations of electromyography in the quantitative study of skeletal muscle function. American Journal of Orthodontist, 1961, 47, 521-530.

Sato, M. Some problems in the quantitative evaluation of muscle fatigue. Journal of Anthropological Soc., Nippon, 1965, 73, 20-27 in Kadefors, R. and Petersen, I. Electromyography, 1970, 1, 45-68.

Scherrer, J., and Bourguignon, A. Changes in the electromyogram produced by fatigue in man. American Journal of Physical Medicine, 1959, 38, 148-158.

Scott, R. N. Myo-electric energy spectra. Medical and Biological Engineering, 1967, 5, 303-305.

Sheer, D. E., Kirkpatrick, D. E., and Dyck, J. W. Human performance capabilities in full pressure suits. Unpublished report, NASA Johnson Space Center, 1971.

Seyforth, H. The behavior of motor units in voluntary contraction. I. Kommisjon Has Jacob Dybwad, 1940 in Basmajian, J. V. Muscles Alive. Baltimore: The Williams and Wilkins Co., 1967.

Sloan, A. W. Electromyography during fatigue in healthy rectus femoris. South African Medical Journal, 1965, 39, 395-398 in Basmajian, J. V. Muscles Alive. Baltimore: The Williams and Wilkins Co., 1967.

Tomita, T. Studies in the fatigue of muscles. 1939 in Gregg, L. W., and Jarrard, L. E. Changes in muscle action potentials during prolonged work. Journal of Comparative and Physiological Psychology, 1958, 51, 532-535.

Travis, L. E. and Lindley, D. B. The relation of frequency and extent of action currents to intensity of muscular contraction. Journal of Experimental Psychology, 1931, 14, 359-381.

Troup, J. D. G., and Chapman, A. E. Analysis of the wave-form of the electromyograph using the analyzer described by Fitch (1967). Electromyography, 1972, 12(4), 17-24.

Walton, J. H. The electromyogram in myopathy: analysis with the spectrometer. Journal of Neurological Neurosurgery and Psychiatry, 1952, 15, 219-226.

Zhukov, E. K., and Zakharyants, J. Z. Electrohpysiological data concerning certain mechanisms of overcoming fatigue. Journal of Physiology, U.S.S.R., 1960, 46, 819-827 in Basmajian, J. V. Muscles Alive. Baltimore: The Williams and Wilkins Co., 1967.