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POWER SPECTRAL DENSITY ANALYSIS OF THE ELECTROMYOGRAM FROM A WORK TASK PERFORMED IN A FULL PRESSURE SUIT

A Dissertation Presented to the
Faculty of the Department of Psychology
of the University of Houston
in Partial Fulfillment of the
Requirements for the Degree of
Doctor of Philosophy

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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16. Abstract

Surface electromyograms (EMG) taken from three upper torso muscles, the bicep brachii, deltoideus, and trapezius, during a push-pull task were analyzed by a power spectral density technique to determine the utility of the spectral analysis for identifying changes in the EMG caused by muscular fatigue. The results confirmed the value of the frequency analysis for identifying fatigue producing muscular performance. More specifically, the data revealed (1) reliable differences between muscles in fatigue-induced responses to various locations in the reach envelope at which the subjects were required to perform the push-pull exercise, and (2) the differential sensitivity of individual muscles to the various reach positions; i.e., certain reach positions imposed more fatigue-related shifts in EMG power than did others. In addition, it was found that a pressurized space suit changed the pattern of normal shirtsleeve muscle fatigue responses in all three of the muscles.

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POWER SPECTRAL DENSITY ANALYSIS OF THE ELECTROMYOGRAM

FROM A WORK TASK PERFORMED IN A

FULL PRESSURE SUIT

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Finally, the author wishes to dedicate this dissertation to his wife, Jean. Her perseverance and moral support, not to mention the nimbleness of her fingers on the calculator keyboard during the reduction of the data, greatly contributed to the success of this investigation.

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ABSTRACT

The power spectral density analysis of EMG recordings from the bicep brachii, middle deltoideus, and upper trapezius of the right torso from four subjects performing a push-pull task at various reach positions in the right reach envelope in a space suit and in shirtsleeves revealed reliable differences between muscles in fatigue-induced responses to individual reach positions, and a differential sensitivity in responses of individual muscles to the various reach positions in the reach envelope.

In the pressurized space suit, the bicep brachii was most affected by the encumbrance. Considering the differences in EMG power between the space suited condition and the shirtsleeve baseline, the bicep brachii registered an increase in power in both the 10-31 hertz band and 61-93 hertz band at all seven reach positions as a result of 1 1/2 minutes of work. However, the trapezius muscle showed a decrease in EMG power at several of the reach positions (as did the deltoideus), indicating a beneficial rather than detrimental effect from the pressurized space suit. This paradoxical finding resulted from a peculiar characteristic of the space suit design which minimizes the muscular effort required to hold the arm in positions above shoulder level. For the positions in which the trapezius muscle registered an increase in EMG power, as opposed to the positions mentioned above, a different approach to the task by the subjects was judged to have caused the difference. Important to this finding is the fact that the spectral analysis method verified the consequences of a minor task procedural difference among the subjects that was observed during the performance of the task.

A graphical comparison of the EMG data from two frequency bands, the 10-31 hertz band and the 61-93 hertz band, showed what appeared to be a difference in the distributions of data. When the 10-31 hertz band data were plotted on reach positions to show a linear trend, the 61-93 hertz band data plotted on the same abscissa showed a curvilinear trend. This apparent difference in the distributions of data in the two frequency bands lends support to Chaffin's (1969) conclusion that separate processes are responsible for the EMG power shifts in the two frequency bands.

A consolidation of the data into more general reach areas, i.e., four reach areas versus the seven reach positions, was attempted to determine if this would provide more useable data for work place and task design purposes. The consolidation of the data did provide more practical visibility into the potential usefulness of the muscle fatigue data in the definition of work space, tasks, procedures, and even muscle conditioning programs.

The task requirements of this study were not of the fatiguing nature of many studies in the literature designed to exact near maximum muscle contractions during test periods. And, this is as it should be for operational purposes where fatigue develops over a period of hours rather than minutes. The absence of an overly demanding task may have been instrumental to the finding of few statistically significant EMG power shifts, i.e., the subject's muscles were not sufficiently fatigued to show significant shifts. However, the data also suggest that the relationship of muscles to reach positions may have had a significant effect on the absolute number of significances. The results suggest a uniqueness of muscles in their responses to the work task. Muscles are shown to be different in their response patterns to reach positions. Moreover, the data indicate that the individual muscles were rather specific in their responses to different reach positions.

An evaluative technique that can be shown to provide information useful to the purpose of limiting muscular fatigue and its concomitant effect on both man and his work has practical utility. In this study, the spectral density analysis technique has shown the capability of providing such information.

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CHAPTER I

INTRODUCTION

Purpose

The primary purpose of this study was to determine the operational feasibility of a power spectral density analysis technique for evaluating muscle fatigue produced by a work task. Of specific interest was the feasibility of the technique to evaluate physical activity in a full pressure suit like the ones used recently for extravehicular activity in the Skylab program and earlier in the moon landing program. However, it was planned to collect shirtsleeve data also, and the findings from the two conditions would have applicability to work tasks requiring little or no constraint to body movement, as well as tasks wherein body movement constraints, such as the space suit, may be a prime factor in changing the fatigue related aspects of the task.

A secondary purpose was to evaluate muscle/work task relationships peculiar to this study; more specifically, how the task related to the fatigue of a particular muscle, and how muscles displayed inter-muscle differential sensitivity to the task.

As reported by Chaffin (1969a, 1969b), several studies in the last decade have shown that spectral analysis of muscle electrical activity is useful for demonstrating some unique features about muscle responses to fatigue-inducing work. For example, as a muscle becomes tired from work, the electrical power, i.e., the squared amplitudes of the muscle potentials detected from the skin, shifts from the middle frequencies (40-70 hertz) to the lower frequencies (30 hertz and below). This evidence points to the utilization of the spectral analysis technique in many practical situations where specific information concerning muscle condition is important to the design of work areas, tasks, equipment, procedures and the like.

To provide a basis for investigating the feasibility of the spectral analysis technique, the following hypotheses were proposed:

Hypothesis 1: The space suited condition will show a significantly greater shift in muscle electrical power than the shirtsleeve condition.

Hypothesis 2: Muscles will show both inter- and intraindividual differences in response to the various parts of the work task.

Hypothesis 3: The power spectral density technique for analyzing fatigue-related muscle electrical data will be shown technically feasible from an operational standpoint.

Problems in Defining and Measuring Fatigue

Conklin and Freeman (1939) state that fatigue is one of the most troublesome disturbers of human efficiency. "Most people", they say, "know what it is to be tired..." and people also assume that the study of fatigue "...is a relatively simple matter." However, only since the turn of this century have there been planned efforts to achieve efficient use of people performing fatigue-induced work. Chaffin (1967) provides a historical review of the development of methods for predicting physical fatigue in industrial operations. These methods run the gamut from personnel selection, i.e., selecting only people capable of performing at the speed and load called for, to measurements of output degradation, to the utilization of physiological measures, e.g., heart rate and oxygen consumption.

Although fatigue is recognized universally as a basic human frailty, there is no universally accepted definition of fatigue. Moore (1942) says: "What fatigue is, no one knows; the word is of the nature of such terms as intelligence, emotion and instinct: a name that is glibly used to cover a multitude of states..." Ricci (1967) states that fatigue may never be defined in precise terms because it is a conglomerate of characteristics. Also, Basmajian (1967) observes that fatigue is a complex phenomenon or perhaps a complex of numerous phenomena.

Bartley (1947) in his book presents a thorough review of the literature on fatigue both from the physiological and psychological viewpoints. He summarizes succinctly: "...(the) views of fatigue...have been varied, fragmentary, and highly inconsistent." Most of the psychological texts reviewed saw fatigue in terms of the work situation characterized by decreased capacity for work and the manifestations of physiological modifications. Some of the texts included a subjective state called "feelings of weariness" which has its prime effect on one's motivation to do something. Murphy (1935) even proposes that fluctuations in work capacity may not be fatigue at all, but simply inattention stemming from lack of interest and boredom.

Ricci (1967) affirms that fatigue causing factors are legion and that psychological factors are dominant. Cameron (1971) says that "...attempts to measure fatigue objectively are often frustrated by what are usually called 'motivational factors'." The subject makes an extra effort to resist performance decrement. Herein lies an advantage of studying fatigue in more localized areas such as individual muscles or composites. Changes in electrical activity within the affected muscles are measurable even though the outward signs of muscular fatigue may be lacking.

Of the physiological texts dealing with fatigue, Bartley (1947) summarizes thusly: "...fatigue is taken as something that happens during activity in muscle and nerve to diminish its activity." To account for the something that happens in the muscle, two theories of muscular fatigue exist, a chemical theory and a central nervous theory. The chemical theory looks upon the decrease in energy reserves and increase in waste products in muscle fibers as the cause of fatigue. On the other hand, the central nervous theory views chemical changes as merely a trigger which causes nerve impulses to pass along sensory paths to the brain where they are perceived as fatigue and thus cause inhibitions in the "control and movement" centers. Consequently, there is a decrease in the frequency of action potentials and a decrease in force and rate of muscular contraction (Grandjean, 1971).

In the physiology texts considered by Bartley (1947), changes in muscles and nerves are specified not for the purpose of defining fatigue, but more in the sense of presenting evidence of fatigue. For example, Bartley quotes from Bard, "Fatigue is due, in part at least, to the fact that after prolonged activity, each fiber in the muscle is able to develope less tension when it contracts." Also, from Bainbridge and Menzies, "If a muscle be repeatedly stimulated, the latent period gets longer, the height of the contraction diminishes and the time for relaxation to occur is prolonged."

From the work physiology viewpoint, physical activity is generally considered in terms of metabolic rate, and the limit for sustained physical activity is primarily a function of an individual's maximum oxygen utilization rate. However, the use of this index is limited because physiological indices such as oxygen consumption, heart rate, et cetera, exhibit poor sensitivity to heavy work loads of relatively short duration (Ramsey and Karnosiewicz, 1969). But more importantly, for many activities where more localized muscle groups are of interest, e.g., upper arm and forearm extensors and flexors, shoulder abductors and elevators, shoulder girdle elevators, et cetera, there is no easily applied technique for determining the maximum oxygen uptake of specific muscle groups (Chaffin, 1969b). For these activities, a more sensitive or localized measurement technique must be used. One such technique is electromyography (EMG). The EMG approach is "...based on the concept that the electrical action potentials emitted by a muscle when it is contracting can be...analyzed and, as such, are objective indicators of the degree of muscle fatigue." (Chaffin, 1969b). Ramsey and Karnoziewicz (1969) add that when the EMG is properly applied and interpreted, it provides an excellent method for validating task requirements when effort is such that the more global physiological indices do not provide adequate sensitivity.

CHAPTER II

BACKGROUND AND STATUS OF EMG RESEARCH

EMG and Fatigue

Electromyography (EMG), the recording of electrical output from muscles, has been used since its inception in the study of fatigue (Basmajian, 1967). Lippold, Redfearn and Vuco (1960) affirm that the sequence of physiological events that occur in muscles from continued activity may be termed muscular fatigue and that such events include: 1) changes in the shape and size of muscle action potentials, and 2) changes in the organization of muscle electrical activity, e.g., synchronization of motor unit firing and migration of muscle activity. In their research on the electromyography of fatigue, they found that the amplitude of action potentials from a muscle increased when it was subjected to continuing voluntary contraction. Lippold (1952) and Bigland and Lippold (1954a, 1954b) showed that a linear relationship exists between the level of muscle activity and the strength of voluntary muscle contractions. Lippold's coefficients of correlation were as high as +0.99. Eason (1960) also found that the level of muscle activity increased progressively with time in both active and passive muscles. Merton (1954), in a definitive study of voluntary strength and fatigue, used the EMG to show that the site of fatigue resulting from intense but short duration contractions is peripheral, i.e., within the muscle. Concerning fatigue, it is undecided whether loss of muscle contractibility is due to a drop in electrical innervation of the muscle fibers or because the fibers become biochemically incapable of maintaining their contraction. Merton's results showed that during extreme fatigue, the muscle action potentials did not diminish in amplitude even though there was a large fall in contractile power in the muscle. Thus, his interpretation was "...that the chemistry of the contractile process becomes defective during fatigue...although normal action potentials pass over the fibers, they cannot be made to contract." Merton also showed that blood supply is the significant factor in the short term strength of a muscle. However, he adds that for the skillful and repetitive movements, deterioration in performance may well be central in origin.

All of the above studies used surface electrodes and Eason (1960) states that the interpretation of the surface EMG requires reference to studies of single motor unit activity during muscular contraction. Eason cites the study of Lindsley and the study of Seyffarth both of which have shown decreases in the amplitudes of the action potentials of single motor units during sustained contraction. Both Eason and Gregg and Jarrard (1958) have advanced a recruitment hypothesis to account for the increases in action potential amplitudes found with surface electrodes.

The Integrated EMG

Initially, and even now in some clinical settings, the EMG was evaluated visually by a trained observer who looked at the number of spikes, their height, type, and spatial location, and classified them by an appropriate key. However, for experimental purposes, and as a result of electronic developments, the integrated EMG came into vogue. The integration of muscle potentials is an amalgamation of the simultaneous variations of amplitude and frequency into a single measure, and thus, is a convenient way of collecting muscle electrical data (Grossman and Weiner, 1966). The principal advantage of the integrated EMG is the convenience of an immediate quantitative readout (Basmajian, 1967).

According to Basmajian (1967), the first useful information produced by the integration technique was from the work of Bigland and Lippold (1954a). Since then, however, the integrated EMG has been used extensively in many areas of research, and especially in ergonomics and human factors research.

In a study involving a weight-lifting task, Small and Gross (1958) found that the integrated EMG, measured from the bicep brachii, increased as a function of both the amount of weight lifted and the rate at which it was lifted. They measured both the active and passive biceps and found a similar relationship in the passive arm, although the magnitude of the change was much smaller than in the active arm.

In a similar study, Gregg and Jarrard (1958) also used a weight-lifting task but measured the EMG from five separate muscle groups: the right and left forearm flexor carpi radialis, the right and left bicep brachii, and the left trapezius. They hypothesized that the muscles involved in lifting would show increases in the integrated EMG as well as the muscles less directly involved. Their results substantiated their hypothesis. The integrated EMGs increased as a function of weight lifted and as a function of the duration of the work task. In addition, they found EMG level increases in all five muscle groups; however, the muscles showed differential sensitivity to the weight lifting task with the flexors exhibiting the largest level increases and the trapezius the least. As mentioned previously, Gregg and Jarrard proposed a recruitment phenomenon as the underlying mechanism to account for the increases in the integrated EMG over the prolonged work period.

Ramsey and Karnosiewicz (1969) used the integrated EMG as a measure of the physiological costs for three muscle groups activated during the practical task of cranking. The muscle groups used were the brachioradialis, the triceps, and the anterior and posterior deltoids. All three of their major independent variables: crank handle radius, torque resistance level, and height of the crank in relation to the body, were significantly related to the level of effort required. The authors analyzed their results in terms of potential impact on the design of cranking mechanisms used in work environments and the need for proper man-machine integration.

A recent addition to the literature on the practical applications of the integrated EMG has been the study by Khalil (1973). He used four muscle groups and both static and dynamic loading tasks. The muscles measured were the bicep brachii, tricep brachii, brachioradialis, and deltoideus. The static load task was that of maintaining a constant torque - four levels were used - on a steel socket for a fixed period of time using a calibrated torque wrench. The dynamic load task involved a cranking task utilizing five different load settings. Khalil measured the muscles individually and collectively. His results again confirmed that changes in the integrated EMG are proportional to the work load. But more importantly, he showed that the integrated EMG is an effective technique for providing a quantitative index of expended effort useful for evaluating tasks and equipment.

Suggestive Spectral Analysis Research

To date, studies using frequency analysis for the evaluation of muscle potentials have been few, even though the technique was seen to have particular merit at least a decade ago. And, only in the last few years has the technique been used in definitive studies of localized muscle fatigue.

Chaffin (1969b, 1969c) has completed several muscle fatigue studies using isometric contractions and spectral density analysis. His research has taken two avenues of interest: 1) providing an easily performed diagnostic procedure for distinguishing fatigue caused by over-exertion from fatigue involving muscle or nerve that is pathologic, and 2) providing a methodology for work place and work method analysis to detect potentially adverse effects of heavy demands on specific muscle groups.

Concerning the first area of interest, Chaffin (1969a) used isometric and repetitive sequence tension on the bicep brachii of both pathologic symptomatic and asymptomatic individuals and found that 1) excessive demands on a muscle shifts the frequency spectrum significantly towards the lower frequency bands, i.e., below 30 hertz, and 2) that in the case of most common myopathies and neuropathies, the EMG spectrums are shifted towards higher frequencies when compared to asymptomatic individuals. He concluded that spectrum analysis "...appears to provide a diagnostic tool of immense potential to the industrial physician."

As for the second area of interest involving methodology for work place and work method analysis, Chaffin (1969b) used the isometric tension procedure to determine the relationships between EMG amplitude shifts in the bicep brachii brought on by heavy exertion demands, and 1) manual performance capability, 2) magnitude of hand tremor, and 3) different work/rest ratios. He found that amplitude shifts to the lower frequencies were coincidental with subjective muscle discomfort ratings, decreased eye-hand coordination precision, and increased hand tremor. The investigation of work/rest ratios determined that a ninety second/ninety second work/rest ratio provided a longer total working time than did a fifteen/fifteen or forty-five/forty-five ratio due to the effective recovery that takes place with the longer cycles. Chaffin concludes that this type of information has far-reaching implications for work design and that EMG amplitude shifts are objective measures of muscle performance and condition that is directly related to various aspects of job performance.

Chaffin's research prompted the effort in this study to apply the power spectral density analysis technique to work performance in the space suit and to attempt to provide additional supportive evidence regarding the practical utility of spectrum analysis to work performance and work place design.

CHAPTER III

METHOD

General

The independent variable in this study was the muscle action potentials, measured by surface electromyograms (EMG), from four subjects on each of three muscles at the beginning and end of performance on a fatigue-inducing task. For purposes of this experiment, fatigue was operationally defined as follows: If when subjects are given a work task of specified length, an increase in the squared amplitudes of the EMG occurs during the task in a low frequency band, namely, 10-31 hertz, and, or, a decrease occurs in a high frequency band, namely, 61-93 hertz, a process called fatigue is inferred to have caused the changes. This definition corresponds to Underwood's (1957) level-3 explanatory concept, causal identification.

Experimental Design

The experimental design selected for this study was the repeated measures design (Edwards, 1960; McNemar, 1962; Myers, 1966) which is particularly adapted to small subject samples. Subjects are treated as a main effect and therefore individual differences do not inflate the error of measurement term. This handling of subject differences increases the precision of the analysis for it minimizes the effects of day-to-day variance of individuals found by Lippold (1952), and also the effects of between-subject differences found by Chaffin (1969c). Bruning and Kintz (1968) refer to this design as the treatments-by-treatments-by-subjects design because each subject is tested under all combinations of treatments.

The treatments in this study were: 1) conditions, i.e., pressurized space suit versus shirtsleeve, and 2) arm reach positions. EMG data from the instrumented muscles were analyzed separately for each muscle across conditions and reach positions. The two conditions were replicated and counterbalanced as shown in Table 1. The presentation of reach positions within each condition were randomly ordered and the four subjects were randomly assigned to the day-by-condition-by-reach position sets.

Subjects

Most space suit studies involve small samples of subjects because suitable subject populations are relatively restricted, i.e., few individuals are available who have had sufficient experience in wearing and working in the space suit. In addition, a scarcity of space suits for test purposes has further restricted the subject sample because the space suit must fit a subject reasonably well in order to preclude any biasing interference to body movements. Space suits are custom fitted to the anthropometric measurements of astronauts or astronaut-like personnel. Thus, test subjects must each closely approximate the physical attributes of the individual that a particular suit was designed for. As a consequence of these rather rigid constraints, only four subjects were used in this study. Three were experienced test subjects, and the fourth was a University of Houston student.

Based on the requirements of good space suit fit, and training and experience in the space suit, the subjects were chosen in accordance with the following criteria:

TABLE 1

EXPERIMENTAL DESIGN

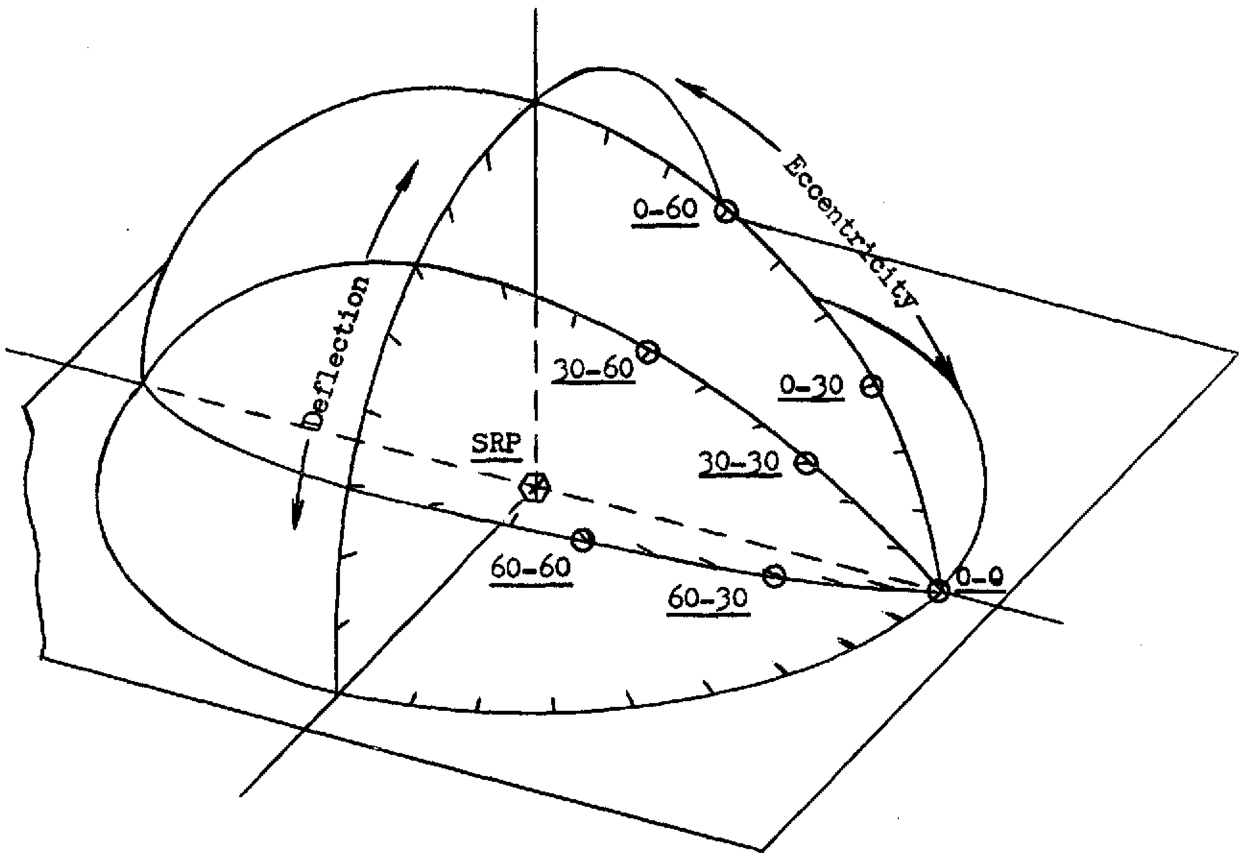
	Reach Positions	Days: 1	2	3	4
		Conditions: Shirtsleeve	Suit	Suit	Shirtsleeve
S_1	R_1				
	R_2				
	⋮				
	R_7				
S_2	R_1				
	⋮				
	R_7				
⋮					
S_4	R_1				
	⋮				
	R_7				

1) Must be a volunteer
2) Must be less than 35 hears of age
3) Must be in the anthropometric range of acceptance for an available space suit
4) Must have a current flight physical examination and altitude chamber physical examination
5) Must have sufficient training or experience in the space suit

Concerning space suit experience, the University of Houston student was given several hours training in the space suit, plus additional hours of experience during the time that test procedures were being finalized for this study. Prior to training, he was provided a flight physical and high altitude chamber training.

Task and Apparatus

A reach task was used in this study to provide the fatigue related EMG measures. The reach task consisted of a push-pull operation, primarily involving the shoulder and arm, for a specified length of time at each of seven reach positions in the right front quadrant of the subject's reach envelope. The reach positions are pictorially represented in Figure 1. As shown, seven reach positions were used: 0-0, 0-30, 0-60, 30-30, 30-60, 60-30, 60-60. Each position is defined in terms of an angular deflection and eccentricity. For example, 0-30 represents 0° in angular deflection and 30° in eccentricity. Likewise, 60-60 represents 60° angular deflection and 60° eccentricity. Each of the subjects performed the push-pull operations in shirtsleeves and in an Apollo-type pressure suit inflated to 3.7 pounds per square inch,



Note: SRP denotes Sternum Reference Point

FIGURE 1

PICTORIAL REPRESENTATION OF THE REACH POSITIONS

ON THE RIGHT REACH ENVELOPE

differential.

To derive the fatigue related EMG measures, the device shown in Figure 2 was used. This device, as described by Sheer, Kirkpatrick and Dyck (1971), consists of a fixed seat mounted on a hydraulic piston such that the seat can be positioned at any point in the vertical plane. The perimeter arch contains aluminum rods which radiate from 0° eccentricity to 180° eccentricity in 15° increments. The rods are friction held and point to the center of the arch. When the subject is seated in the device, the center of the arch lies in the vertical plane defined by the subject's sternum and in the horizontal plane defined by the seat reference point (see Figures 2 and 3). As the arch is deflected to the side, the intersect of the rods with the sternum remains constant. Thus the device permits a subject to push and pull the rods along lines radiating approximately from the shoulder regardless of the orientation of the perimeter arch.

Apollo Space Suit

A detailed description of the space suit is provided by Sheer, et al. (1971). The space suit used in this study was the A7L model consisting of the following, briefly described, components:

1) Constant Wear Garment - better described as long underwear.
2) Pressure Garment Assembly - the basic pressure shell contoured to and covering the body.
3) Glove Assembly - attachable to the pressure garment at the torso wrist with a slide lock disconnect and incorporating 360° of rotation.

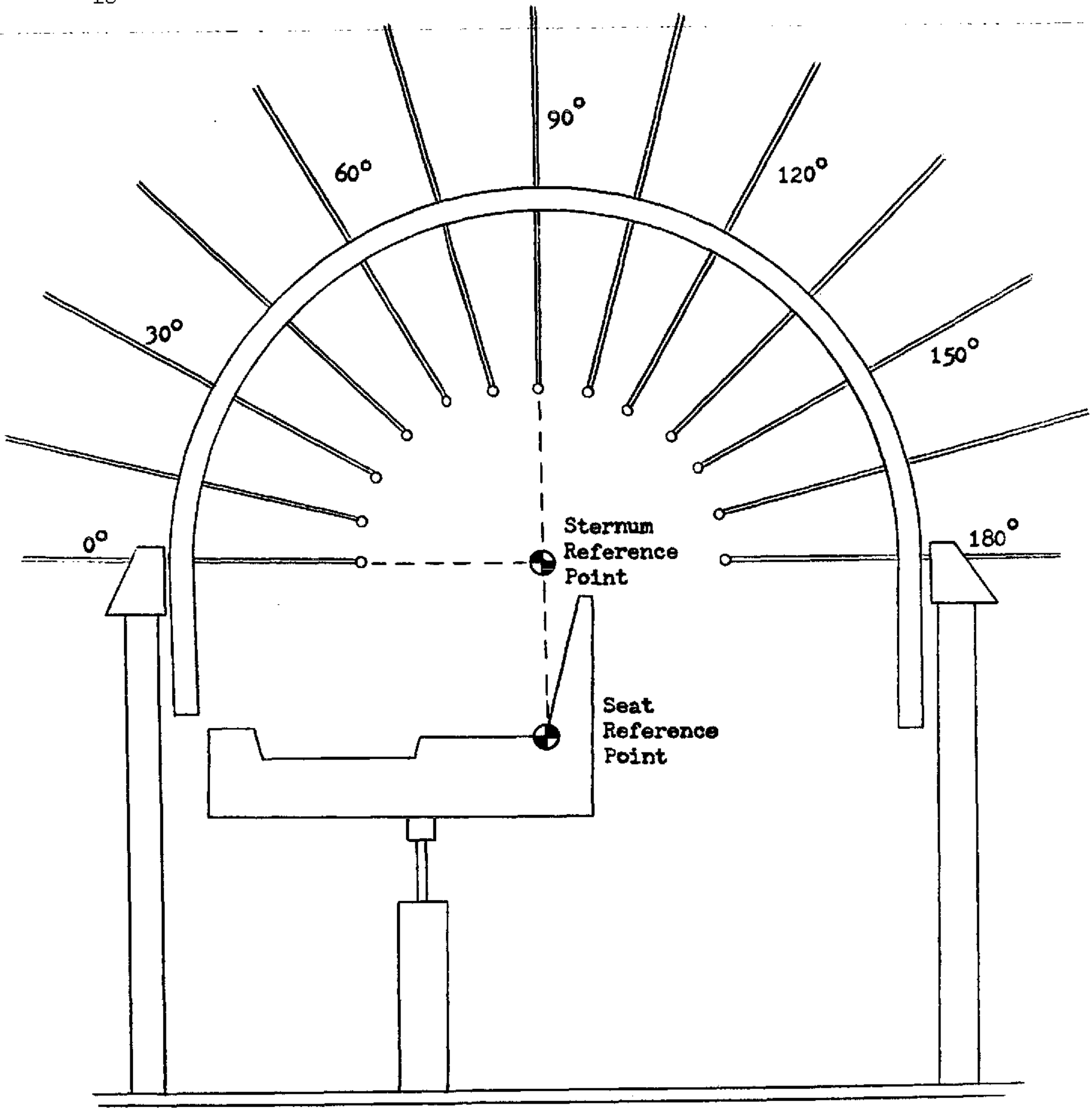


FIGURE 2

REACH MEASURING PERIMETER

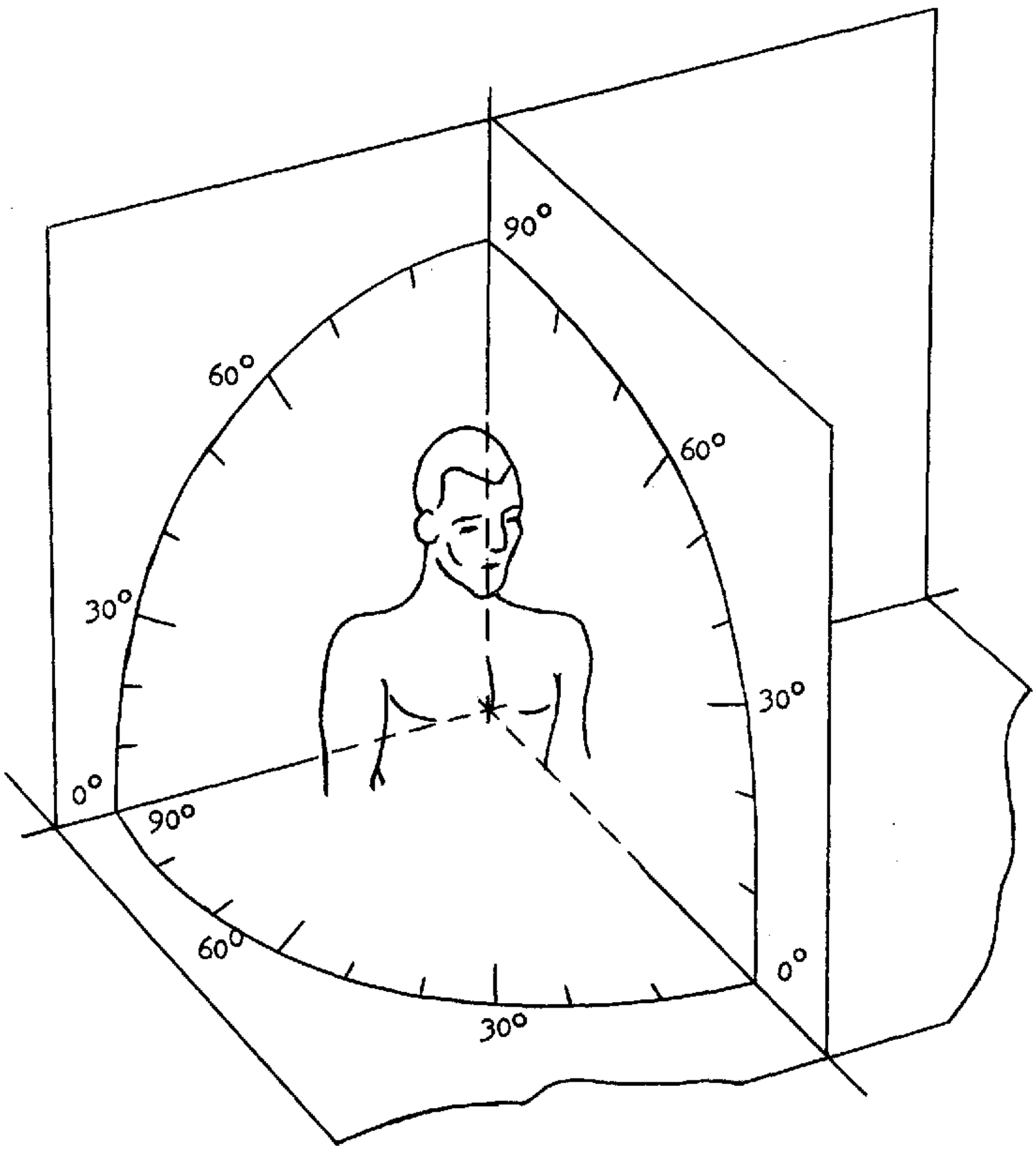


FIGURE 3

REACH PERIMETER SHOWING THE INTERSECTION OF

THE RODS WITH THE STERNUM

4) Helmet Assembly - protective plastic shell for the head which is attached to the pressure garment by means of a neckring lock assembly. The helmet provides a wide range of visibility.

5) Gas Distribution System - distributes breathable air to the helmet area and ventilation to the torso and extremities. Also provides the capability to pressurize the space suit.

6) Protective Coverlayer - beta cloth outer cover for protecting the pressure garment against wear and abrasion and for protecting the astronaut from excessive thermal conditions and micrometeroid penetration.

Voice contacts with the subjects and bioinstrumentation were routed through a communications and biomedical connector on the front of the space suit.

Electromyographic Recording

The surface EMG recordings of muscle potentials were obtained from the right bicep brachii, right middle deltoideus, and right upper trapezius muscles of each subject. Two silver/silver chloride electrodes were placed over the belly of each muscle and spaced approximately 1 1/2 inches, center-to-center. The common electrode was placed on the upper right chest just below the clavical.

The electrode housing consisted of a cup and flange designed to support the electrode above the skin with contact provided by a small sponge impregnated with Ringers solution. The skin contact area was about two square centimeters. The outside diameter of the electrode system was 1 1/8 inches. A double adhesive disk, set on the electrode flange, was used to attach the electrode to the skin.

The electrodes were connected to the amplifiers of an integrated biomedical recording system which included a CRT display, a 1/2 inch magnetic tape recorder, and a strip chart recorder. Electronic filters were inserted between the amplifier and the tape recorder to eliminate baseline excursions due to muscle movement. The CRT and strip chart recorder were used to monitor the amplifier input to the magnetic tape recorder and the input from the tape recorder, respectively. The latter was a check to verify that EMG signals were being put on the magnetic tape. In other words, it was a check on the integrity of the skin-electrode-amplifier-tape recorder system.

The analog data on the magnetic tapes were digitized to provide a computer compatible tape and time-marked strip chart recordings made of the original analog and the analog of the digitized data. The strip chart recordings were used: 1) to compare the fidelity of the digitized data, and 2) to determine the time segments on the digitized tape that were to be analyzed with the power spectral density program. Figure 4 shows the schematic of the muscle action potential measuring and analysis system.

The amplifiers of the biomedical recording system provided a differential input impedance exceeding forty megohms in the frequency band between 0.2 and 100 hertz. The gain of the system was continuously variable from 600 to 4500. For this study, the gain of the amplifiers was set at approximately 2000. The harmonic distortion was less than

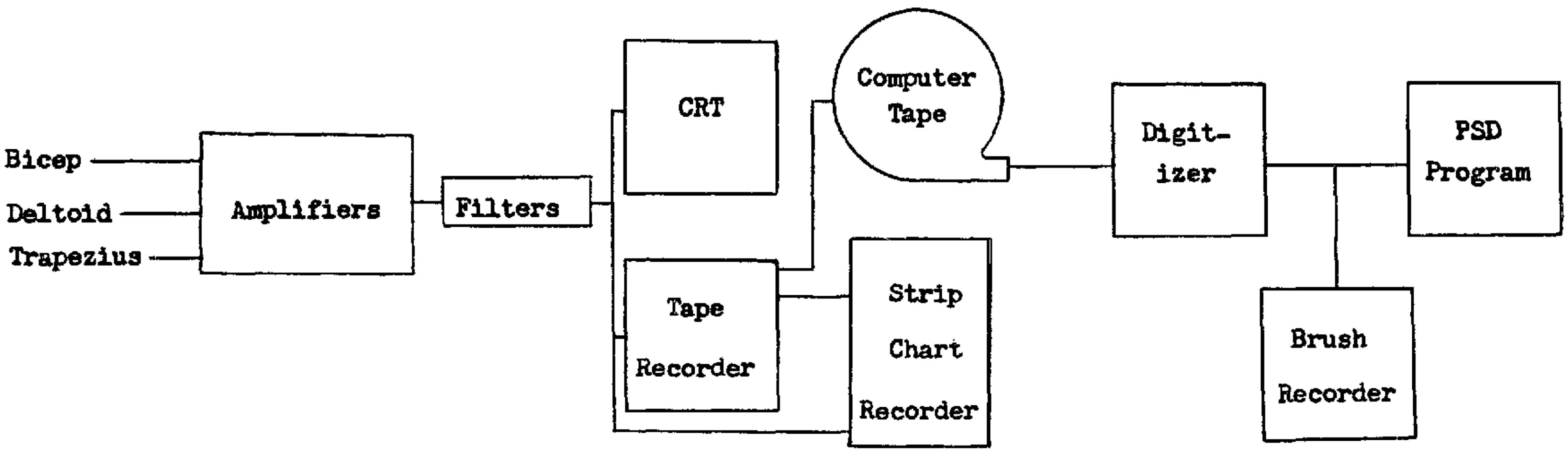


FIGURE 4

EMG MEASURING AND ANALYSIS SYSTEM

1% over the band of 0.2 to 100 hertz, and the response within the same bandwidth was flat within plus or minus 3 decibels.

Treatment of Electromyographic Data

The muscle potentials recorded on the magnetic tapes were first digitized at 500 samples per second and then spectrally analyzed with a power spectral density program on an 1108 computer. The spectral density program converted the time domain data into a frequency domain, categorized each muscle potential into its component frequencies, and then squared, summed and averaged the amplitudes in a frequency band centered at two hertz intervals over the range of 4 to 100 hertz. In simpler terms, the computer summed the squared values of amplitude for each 2 hertz band over the range of 4 to 100 hertz, divided the sum by the width of the band, and printed out the value as a data point. For each subject, the number of data points, totaled across all variables, was approximately 4000.

The two frequency bands used in the analysis of fatigue effects, the 10-31 hertz band and the 61-93 hertz band, correspond approximately to the frequency bands used by Chaffin (1969) and his collegues wherein they found statistically consistent power shifts in response to isometrically-induced fatigue.

To establish a standardized measurement so that the different sets of data could be compared, the sum of the power in each of the two frequency bands was computed as a percentage of the total power residing in the 10-93 hertz band. The percentage values became the basic data with which the various analyses were made.

Procedure

The initial step in the experiment procedure was to determine the noise level of the biomedical recording system without the subject. A shunt was placed across the electrode leads and the system noice measured. The system noise was usually on the order of twenty microvolts or less.

After the noise check, the subjects were prepared for electrode application. The skin over the electrode sites on each of the three muscles was cleaned thoroughly with reagent-type acetone to remove dry skin and oils from the areas. The prepared electrodes were then applied to all sites and a measure of skin resistance taken. If the skin resistance was below 100 thousand ohms (Chaffin, 1969), the subject was connected to the recording system to verify the input of muscle signals to the recording system. However, if resistance was above 100 thousand ohms, either the electrodes were removed and the application process repeated, or the subject waited for a period of time until skin resistance went below the 100 thousand ohms level.

With verification of an acceptable skin resistance level and EMG input to the recording system, the subject was then seated in the reach device to begin a shirtsleeve session, or the subject donned the space suit, was seated in the reach device, and the space suit pressurized to 3.7 pounds per square inch, differential.

When the subject was comfortably seated, the seat was adjusted to place the reference or center of the perimeter arch in the horizontal plane defined by the subject's sternum (see Figures 2 and 3). After establishing the reference point, the subject was restrained in position by a lap belt and a chest strap.

The experimental procedure lasted for four minutes for each reach position. The procedure timeline is shown in Appendix A. The procedure was continued without interruption, except for brief rest periods, through the seven reach positions.

The subject was instructed to grasp the appropriate rod in the reach device and upon signal begin to push and pull the rod with a cycle rate of approximately two seconds until signalled to stop. The work period for each reach position lasted for 1 1/2 minutes. The muscle potentials of the first and last twenty seconds of each work period comprised the data for this study.

At the end of seven reach positions, the subject was given a five minute rest after which the seven reach positions were repeated in reverse order. The reversed replication not only provided additional data points, but served to distribute any sequence effects across muscles.

To minimize the possible effects of time-of-day, subjects were always scheduled for the same time for all four of the experimental runs.

CHAPTER IV

RESULTS

Because the basic data were percentages or proportions, an arcsin transformation was used to make the data more amenable to the analysis of variance. In the interest of consistency, all of the analyses were performed with the transformed values.

The day-to-day effects were analyzed with the Wilcoxon matched-pairs signed ranks test (Siegel, 1956). The first shirtsleeve and first suited runs were combined as were the second shirtsleeve and second suited runs, and a mean value determined for each reach position. The differences in the mean values for the two days were found to be insignificant at the required .05 level.

Initial individual differences were tested using the first shirtsleeve run for each subject tabled with reference to each muscle and the Kruskal-Wallis one-way analysis of variance (Siegel, 1956) applied. The tests showed that no initial differences existed between subjects in EMG response.

To determine the condition of the variances prior to the analysis of variance, Hartley's (1950) F-Maximum test for homogeneity of variances was applied to the data for both the suited and shirtsleeved conditions across both the high and low frequency bands. The results of this analysis are shown in Table 2. One of the F-ratios proved to be just significant at the .05 level. Nevertheless, with the slight risk of a probable Type I error for the suited data in the 61-93 hertz band, the analysis of variance was utilized for hypothesis evaluation.

Six problems were analyzed with the analysis of variance, each of the three muscles in each of the two hertz bands. Tables 3 and 4 show

TABLE 2

F-MAXIMUM TEST FOR HOMOGENEITY OF VARIANCES

Subject	10-31 Hertz		61-93 Hertz	
	Suit	Shirtsleeve	Suit	Shirtsleeve
SAM	760.7	321.2	1086.7	341.8
COV	849.1	135.3	1129.3	348.1
BUR	306.4	243.3	500.9	230.7
BOR	464.6	255.4	299.2	735.9
Ratio	$\frac{849.1}{306.4}$	$\frac{321.2}{135.3}$	$\frac{1129.3}{299.2}$	$\frac{735.9}{230.7}$
F	2.52	2.37	3.77 *	3.20

* = $p < .05$

TABLE 3

ANALYSIS OF VARIANCE OF THE 10-31 HERTZ BAND DATA

		BICEP		DELTOID		TRAPEZIUS	
SOURCE	DF	MS	F	MS	F	MS	F
SUBJECTS	3	81.8	1.68	0.9	< 1	119.8	3.67
REACH POSITIONS	6	127.4	2.61	4.2	< 1	64.4	1.98
ERROR	18	48.8		10.6		32.6	
CONDITIONS	1	293.2	4.12 *	28.9	2.21	2.8	< 1
INTERACTION	6	39.2	< 1	10.5	< 1	53.8	1.46
ERROR	87	71.2		13.1		36.8	
TOTAL	111						

* $p < .05$

TABLE 4

ANALYSIS OF VARIANCE OF THE 61-93 HERTZ BAND DATA

		BICEP		DELTOID		TRAPEZIUS	
SOURCE	DF	MS	F	MS	F	MS	F
SUBJECTS	3	171.2	5.25	21.6	< 1	202.9	2.91
REACH POSITIONS	6	100.9	3.10 *	13.2	< 1	43.1	< 1
ERROR	18	32.6		26.5		69.8	
CONDITIONS	1	293.5	5.08 *	0.0	< 1	10.7	< 1
INTERACTION	6	20.2	< 1	37.8	< 1	32.4	< 1
ERROR	87	57.7		39.5		55.3	
TOTAL	111						

* $p < .05$

the results of the analysis for the 10-31 hertz band and 61-93 hertz band, respectively. Subject differences were not of experimental interest in this study and, therefore, were not considered.

The analysis of the overall effects of conditions (space suit versus shirtsleeve) showed significant differences ($p < .05$) for the bicep muscle but not for the trapezius or deltoid. Graphs of these differences are shown in Figures 5 and 6. Main effects were found for both reach positions and conditions in the bicep muscle, however, interaction effects were lacking. The absence of interaction effects show that subject performance on reach positions was not significantly dependent upon conditions, i.e., the direction and magnitude of a difference attributable to a condition was relatively constant across all of the reach positions. This constancy is reflected in Figure 7 which shows the data plot for the bicep brachii in the 10-31 hertz band. Figure 8 reflects more of a tendency for reach position by condition interaction for the trapezius muscle, however, the interaction is not significant. Figure 9 shows the data plot for the bicep muscle in the high frequency band and the main effect for conditions is again evident. Figure 10 depicts the data trend for the trapezius muscle.

Based on the significant F rations found in the analysis of variance, further tests on the bicep data were appropriate (Guilford, 1956). However, in considering the nature of the work task in this study, the diverse involvement of muscles, and the fact that the test procedure was not designed to exact large penalties in terms of muscular fatigue, additional analyses on the trapezius and deltoid muscles were done for comparison purposes because there were observable peculiarities.

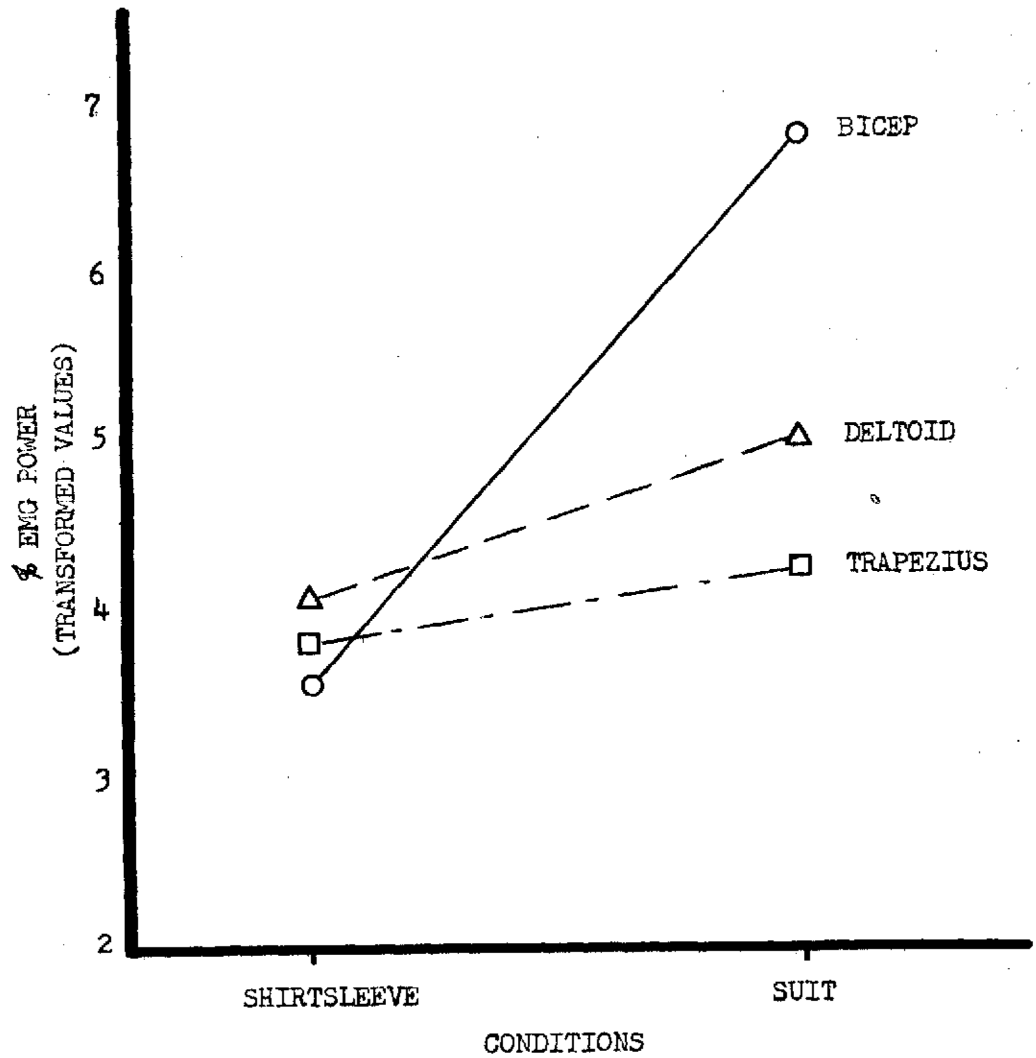


FIGURE 5

MAGNITUDE OF EMG POWER SHIFTS FOR CONDITIONS IN THE 10-31 HERTZ BAND

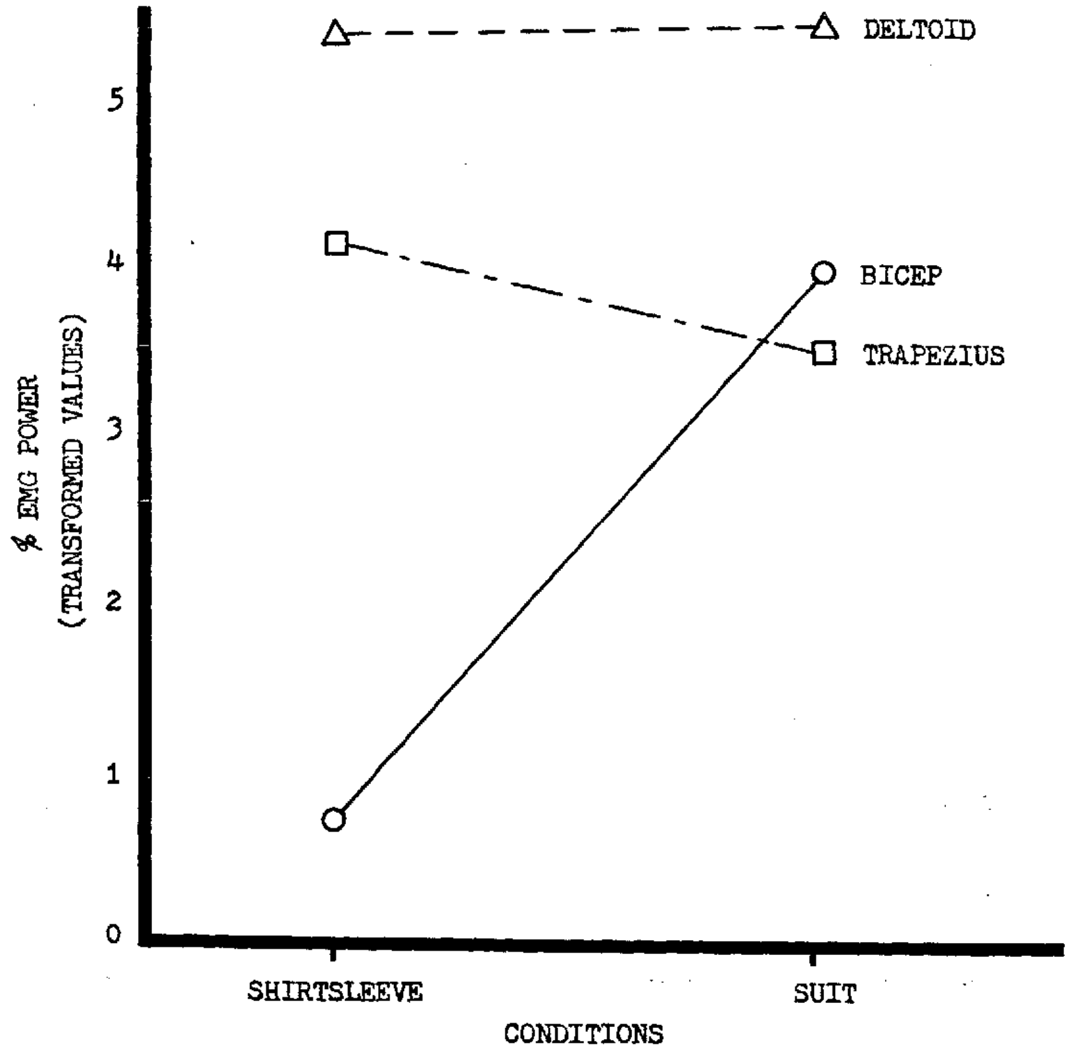


FIGURE 6

MAGNITUDE OF EMG POWER SHIFTS FOR CONDITIONS

IN THE 61-93 HERTZ BAND

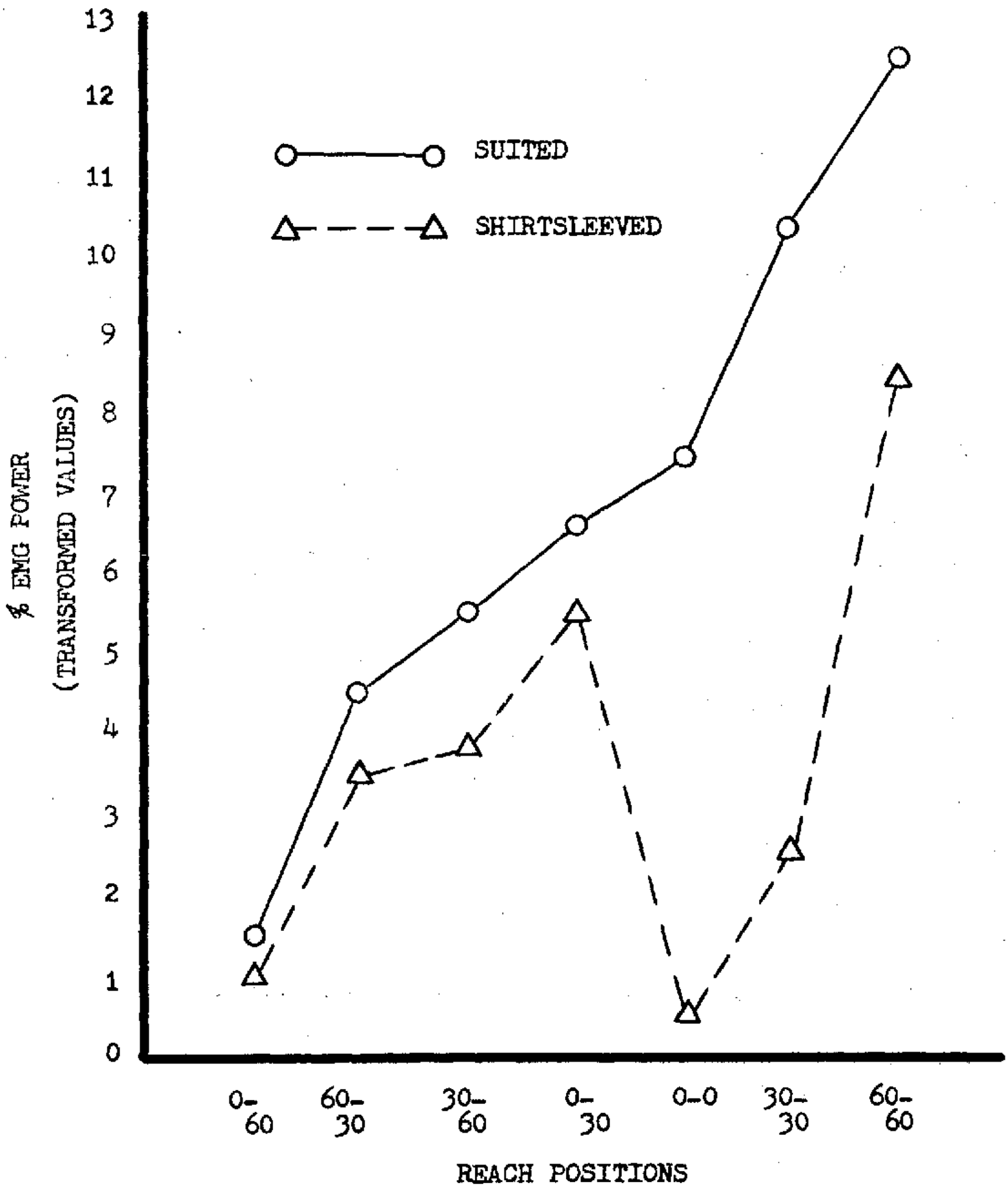


FIGURE 7

MAGNITUDE OF EMG POWER SHIFTS FOR EACH CONDITION

WITH REFERENCE TO REACH POSITIONS FOR THE

BICEP BRACHII IN THE 10-31 HERTZ BAND

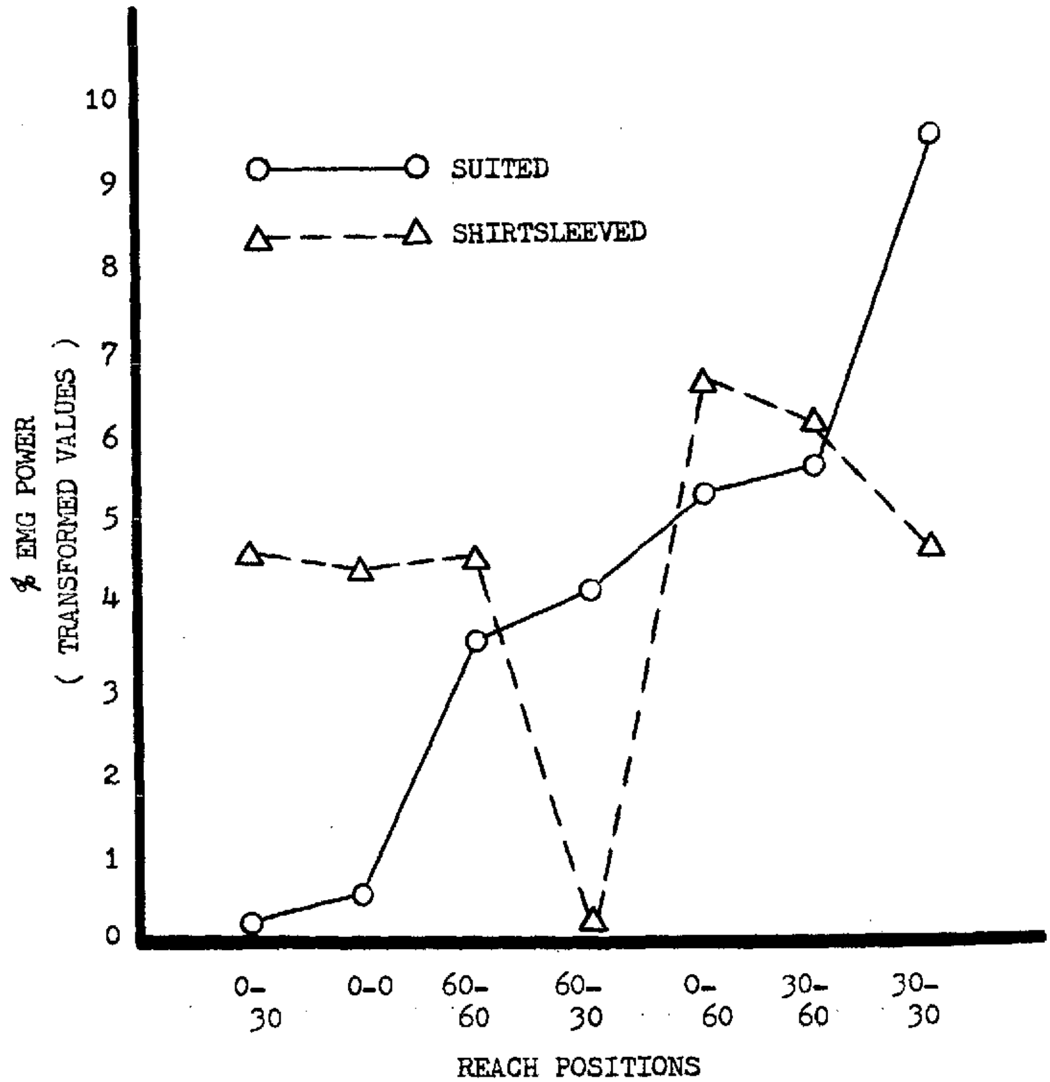


FIGURE 8

MAGNITUDE OF EMG POWER SHIFTS FOR EACH CONDITION WITH REFERENCE TO REACH POSITIONS FOR THE TRAPEZIUS IN THE 10-31 HERTZ BAND

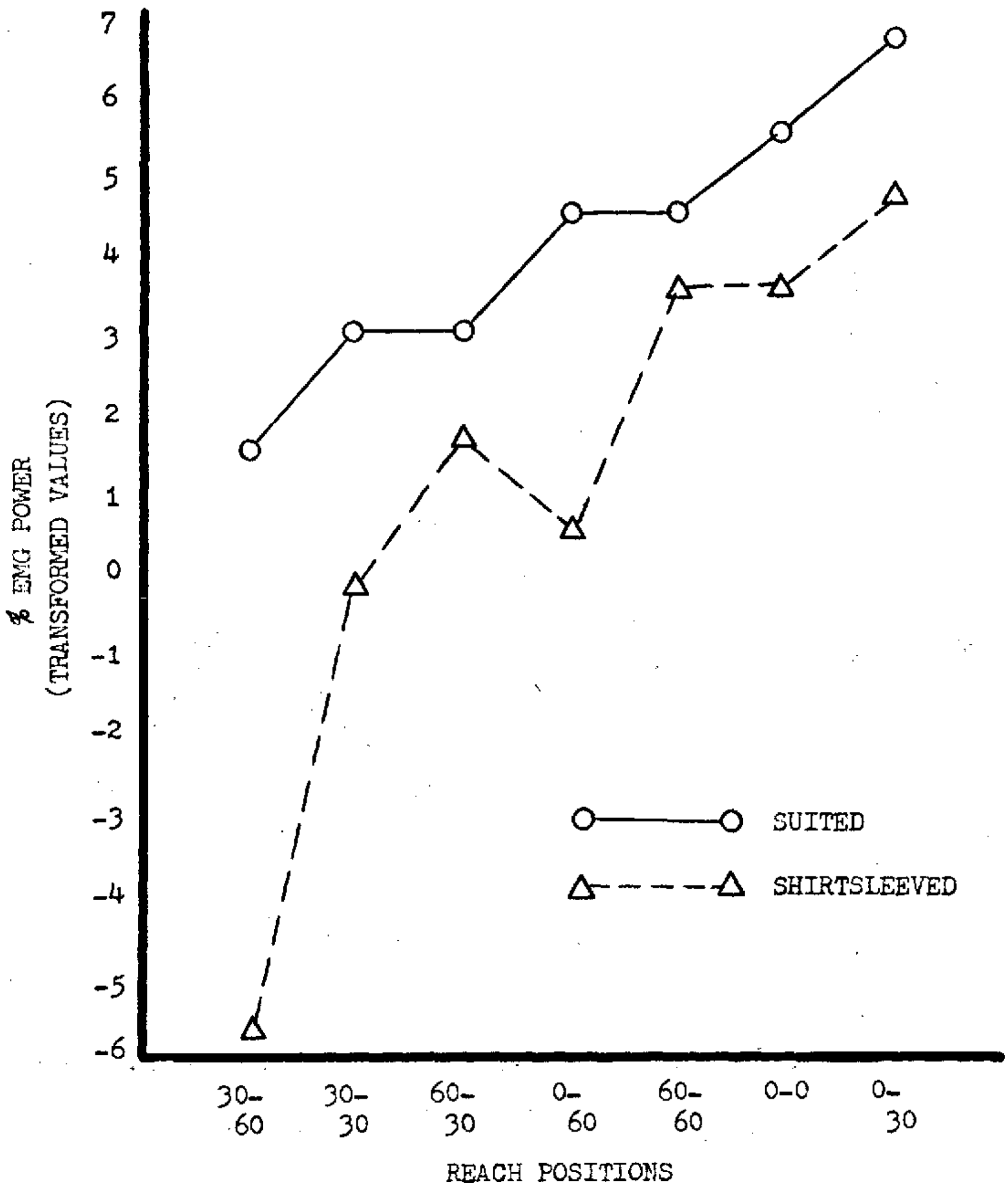


FIGURE 9

MAGNITUDE OF EMG POWER SHIFTS FOR EACH CONDITION WITH REFERENCE TO REACH POSITIONS FOR THE BICEP BRACHII IN THE 61-93 HERTZ BAND

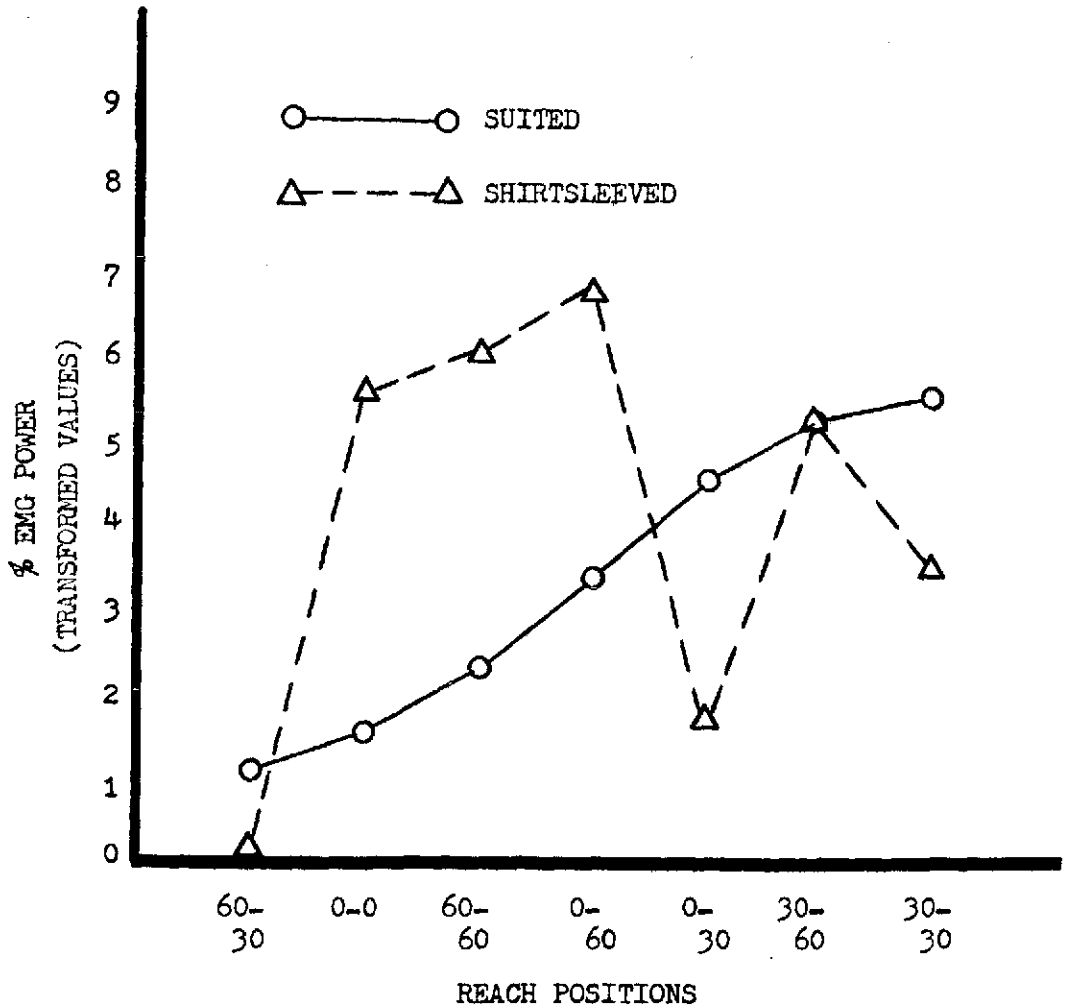


FIGURE 10

MAGNITUDE OF EMG POWER SHIFTS FOR EACH CONDITION

WITH REFERENCE TO REACH POSITIONS FOR THE

TRAPEZIUS IN THE 61-93 HERTZ BAND

A visual comparison of the EMG data indicated that power shifts were greater in shirtsleeves than in the space suit for some reach positions. This indicated that the space suit was compensatory rather than detrimental in some cases. Since the space suit was, in essence, a treatment effect with the shirtsleeve condition a baseline response level, the data were tabled to show space suited effects with the baseline partialled out. The results are shown in Tables 5 and 6. In addition, the plots of the difference data for subjects are graphed in Figures 11 and 12. Each data point represents the mean of two difference values for a particular subject. To determine if there was a significant difference between subjects, performance was dichotomized as either "positive" or "negative" and the instances summed for all the reach positions. Table 7 shows the results. Subjects SAM and BUR responded alike as did COV and BOR, however, the response patterns were in opposite directions. In the 10-31 hertz band, SAM and BUR responded 8 of 14 times with a negative difference indicating a space suit assist in performance, whereas, COV and BOR responded 10 or 14 times with a positive difference indicating the space suit was detrimental to performance. A test of these proportions was significant beyond the .05 level. The comparable proportions for the 61-93 hertz band were also significant beyond the .05 level. To determine whether the space suited condition significantly altered the baseline, the t test (Bruning and Kintz, 1968) was applied to the difference values between conditions for each reach position for both the bicep brachii and trapezius muscles. The results of this analysis are shown in Tables 5 and 6.

TABLE 5

t TESTS FOR DIFFERENCES AMONG REACH POSITIONS MEANS FOR THE 10-31 HERTZ BAND

Muscle	Reach Position	Means Suit	Means Shirtsleeve	Difference
Bicep	0-0	7.5	0.5 *	7.0 *
	0-30	6.5	5.7	0.8
	0-60	1.6 *	1.0 *	0.6
	30-30	10.3	2.4 *	7.9 *
	30-60	5.6	3.9	1.7
	60-30	4.5	3.8	0.7
	60-60	12.5 *	8.5 * * *	4.0
Trapezius	0-0	0.3 *	4.3	-4.0
	0-30	-0.1 *	4.7	-4.8 *
	0-60	5.2	6.6 *	-1.4
	30-30	9.5 * *	4.5	5.0 *
	30-60	5.5	5.7 *	-0.2
	60-30	4.1	0.1 * *	4.0
	60-60	3.3	4.2	-0.9

* = $p < .05$

Note: Under "Suit" and "Shirtsleeve" columns, an asterisk in the same column indicates a significant difference ($p < .05$) between the two values so marked.

TABLE 6

t TESTS FOR DIFFERENCES AMONG REACH POSITION MEANS

FOR THE 61-93 HERTZ BAND

Muscle	Reach Position	Means: Suit	Means: Shirtsleeve	Difference
Bicep	0-30	6.7	4.3 * * *	2.4
	60-60	4.6	3.4 * *	1.2
	0-0	5.3	3.3 * *	2.0
	60-30	3.2	1.8 *	1.4
	30-30	2.9	-0.1 *	3.0
	0-60	4.5	-1.5 * * *	6.0 *
	30-60	1.4	-5.5 * * * *	6.9 *
Trapezius	0-60	3.6	6.7 * *	-3.1
	60-60	2.6	5.9 * *	-3.3
	0-0	1.5	5.6 *	-4.1
	30-60	5.4	5.4 *	0.0
	30-30	5.6	3.5	2.1
	0-30	4.8	1.8 * *	3.0
	60-30	1.1	0.1 * * * *	1.0

* = $p < .05$

Note: Under "Suit" and "Shirtsleeve" columns, an asterisk in the same column indicates a significant difference ($p < .05$) between the two values so marked.

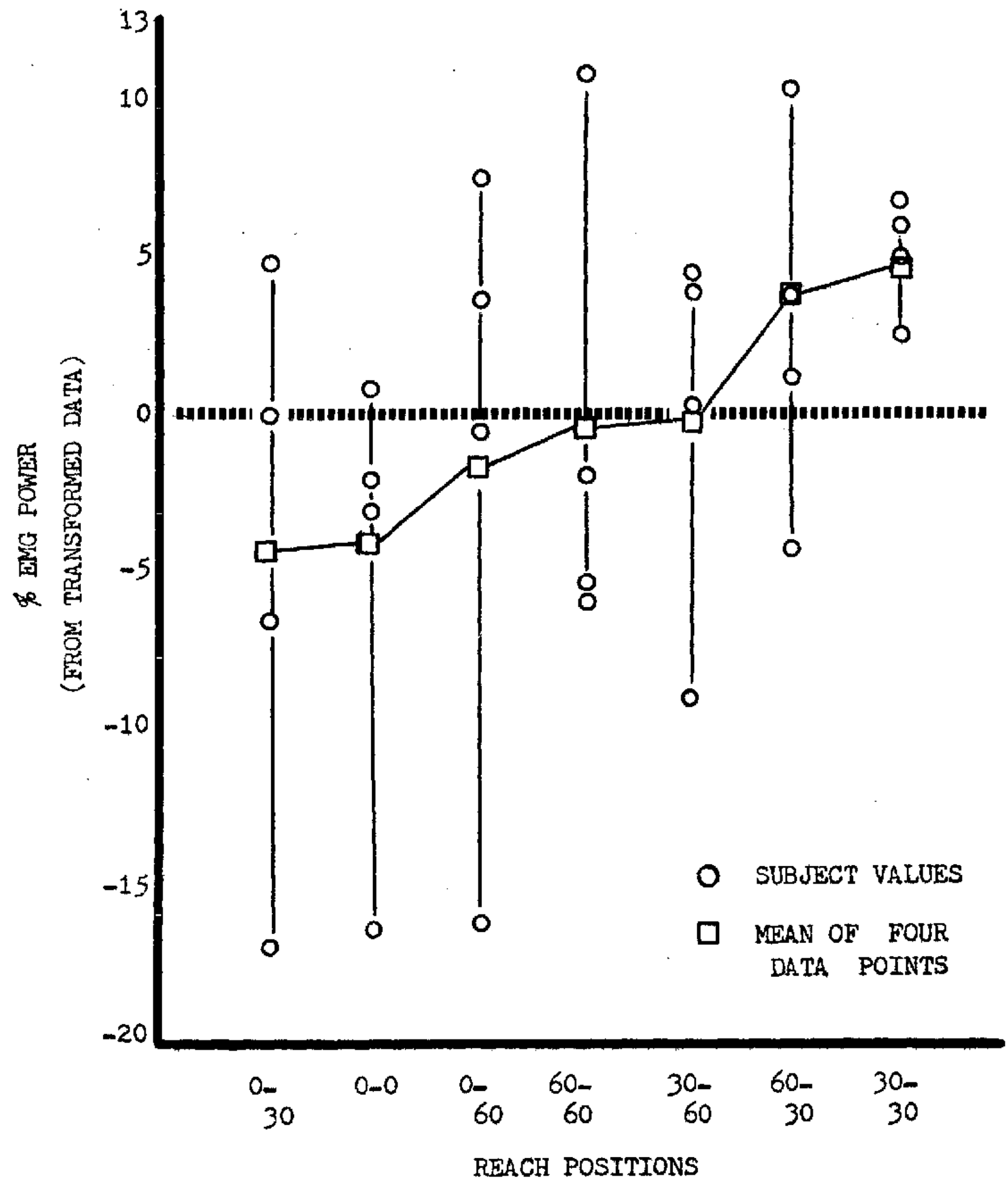


FIGURE 11

PLOT OF EMG DATA POINTS FOR EACH SUBJECT AT EACH REACH POSITION FOR THE TRAPEZIUS MUSCLE IN THE 10-31 HERTZ BAND. DATA POINTS REPRESENT DIFFERENCES FOUND BY SUBTRACTING THE SHIRTSLEEVE DATA FROM THE SUIT DATA

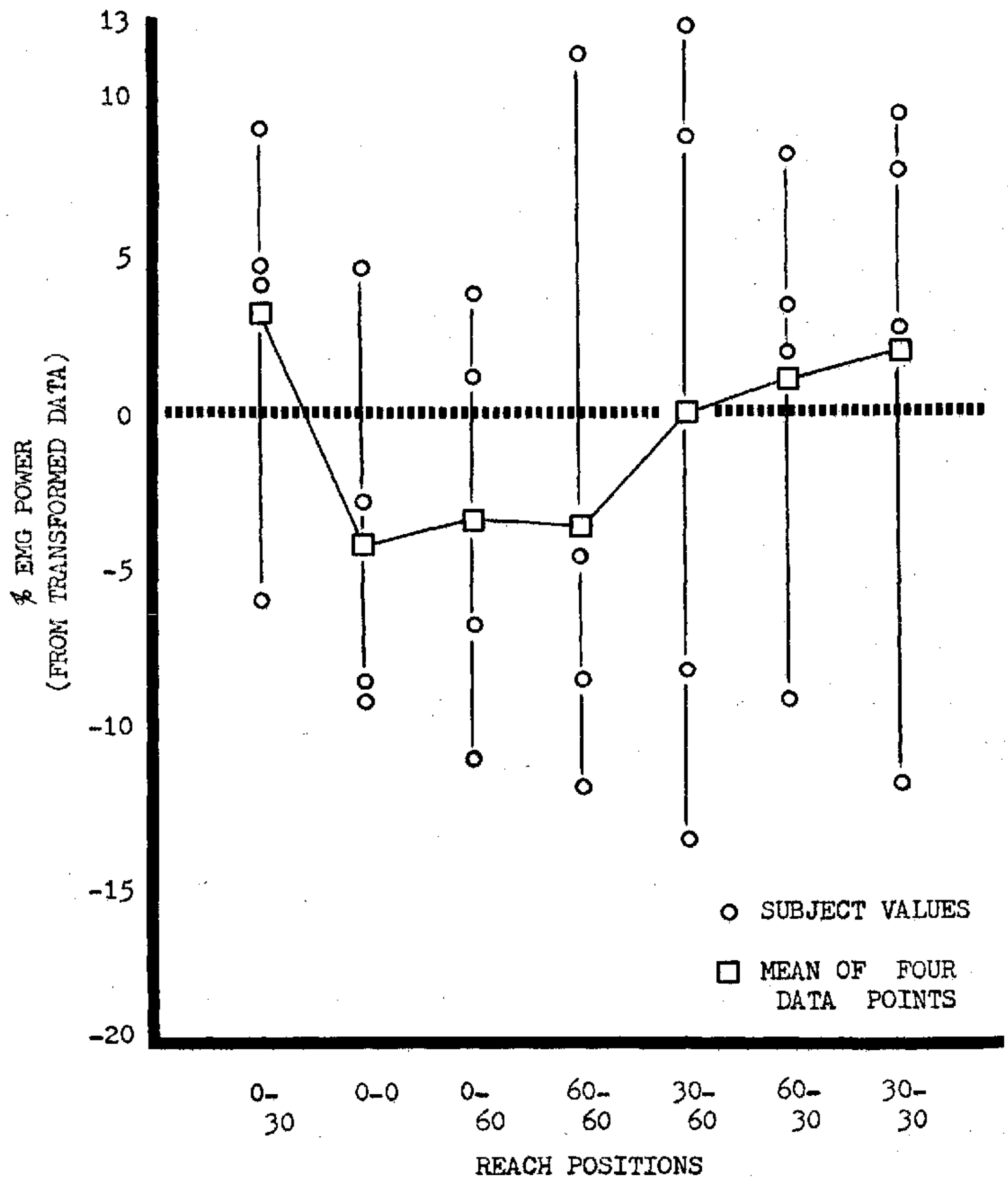


FIGURE 12

PLOT OF EMG DATA POINTS FOR EACH SUBJECT AT EACH REACH POSITION FOR THE TRAPEZIUS MUSCLE IN THE 61-93 HERTZ BAND. DATA POINTS REPRESENT DIFFERENCES FOUND BY SUBTRACTING THE SHIRTSLEEVE DATA FROM THE SUIT DATA

TABLE 7

THE POSITIVE AND NEGATIVE EMG POWER SHIFTS

RESULTING FROM PRESSURIZED SPACE SUIT USE

Hertz Band	Subject	No. of Difference Values Negative	Positive
10-31	SAM	4	3
	BUR	4	3
	COV	2	5
	BOR	2	5
61-93	SAM	6	1
	BUR	3	4
	COV	1	6
	BOR	3	4

Note: A positive difference value means the space suit caused an increase in the EMG power in the particular frequency band when compared with the shirtsleeve condition. A negative values denotes a decrease.

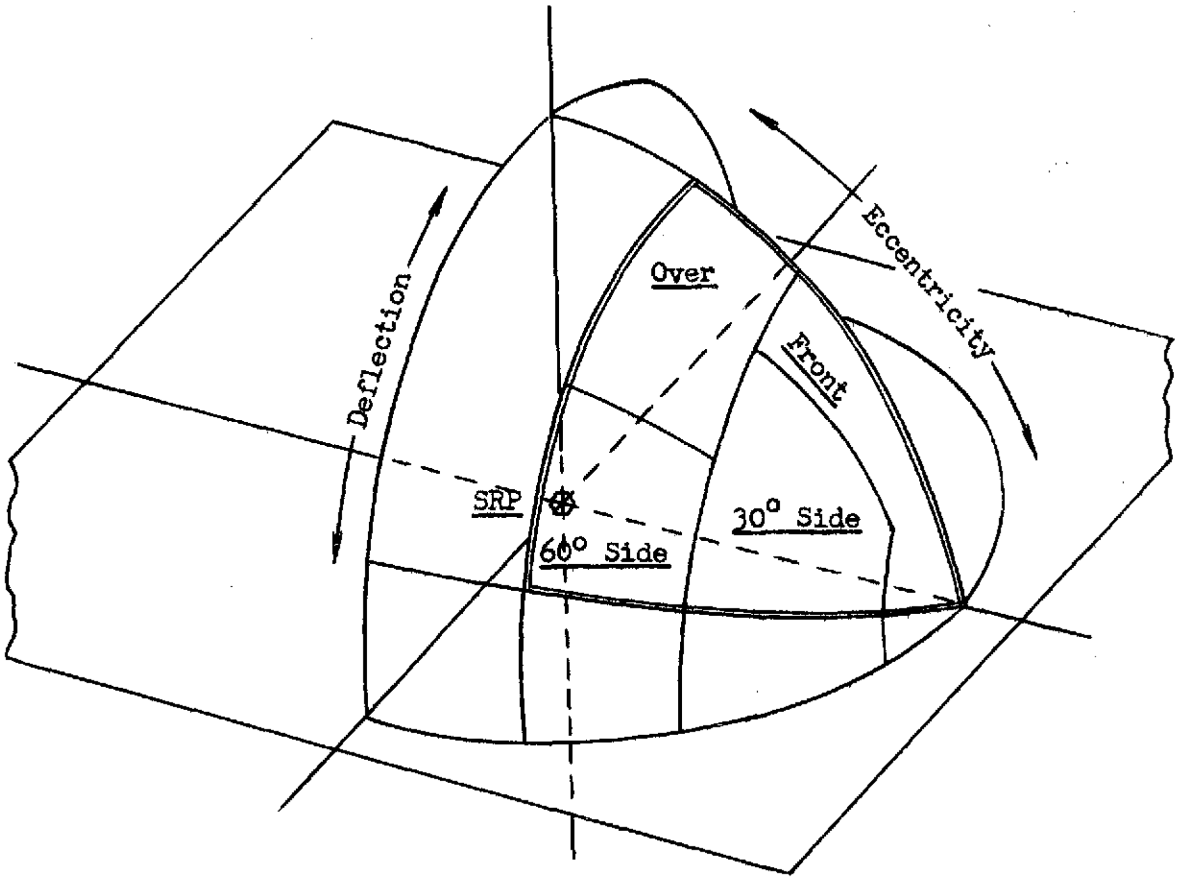
To test the hypothesis that the reach positions were differentially effective in inducing fatigue related EMG power shifts, the t test was applied to the mean differences in EMG response between the various reach positions. The results of this analysis are also shown in Tables 5 and 6.

The data for the reach positions show essentially two things: 1) the effect of the space suit on baseline performance, and 2) the lack of any consistency between muscles on the reach positions that each responds to maximally.

From the outset of the study, an adequate sampling of reach positions in the right front reach envelope was planned with the recognition that such a sample might present such diversity of muscle involvement that a more general categorization, e.g., in front of the body, over the head, and to the side of the body, might be necessary to provide more visibility and sensitivity for practical applications. Therefore, the data were consolidated into four general reach areas as follows (see Figure 13):

1) 0-0 and 0-30 were combined to represent an area in front of the body and to be referred to as "front".
2) 0-60 and 30-60 were combined to represent an area over the head and to be referred to as "over".
3) 30-30 and 60-30 were combined to represent an area 30° to the side and to be referred to as "30° side".
4) 60-60 to be referred to as "60° side".

The data reflecting the consolidation and the results of the Wilcoxon signed ranks test applied to test for differences are shown in Tables 8



Note: SRP denotes Sternum Reference Point

FIGURE 13

PICTORIAL REPRESENTATION OF THE FOUR REACH AREAS

(BOUNDARIES ARE APPROXIMATED)

and 9. In addition, the plots of the data are shown in Figures 14 thru 17.

Considering the shirtsleeve bicep brachii data for the 10-31 hertz band, working at 60° to the side of the body was significantly more fatiguing than working at either the 30° side or front positions. But, in the space suit, working at either side position was more fatiguing than working over the head. This is not to say that working over the head is an easy task in the space suit. It simply means that the bicep brachii is not used extensively in this position. However, the trapezius muscle is used at this position, and an examination of the space suit data in Table 8 reveals the "over" position to be significantly more fatiguing for the trapezius muscle than work to the side of the body.

Figures 18 and 19 were plotted to give a clearer picture of how the space suit affected the shirtsleeve performance. The data points represent a difference computed by subtracting the shirtsleeve value from the space suit value. In the 10-31 hertz band, the response of the bicep muscle to the suited condition was significantly greater ($p < .05$) than the responses of either the deltoid or trapezius muscles. The deltoid and trapezius did not differ significantly from one another. In the 61-93 hertz band, the bicep muscle response again differed significantly from both the deltoid and trapezius muscles. The latter two did not differ significantly from each other. The plots also show clearly which muscles were benefited by the pressurized space suit and in which areas.

TABLE 8

t TESTS FOR DIFFERENCES BETWEEN REACH AREA MEANS

FOR THE 10-31 HERTZ BAND

Muscle	Condition	Reach Areas	Means		
Bicep	Suit	Front	7.0		
		Over	3.6	*	*
		30° Side	7.4	*	
		60° Side	12.5		*
	Shirtsleeve	Front	3.1	*	
		Over	2.5		
		30° Side	3.1		*
		60° Side	8.5	*	*
Trapezius	Suit	Front	0.3	*	*
		Over	5.3	*	
		30° Side	6.8		*
		60° Side	3.3		
	Shirtsleeve	Front	4.4		
		Over	6.1	*	*
		30° Side	2.3	*	
		60° Side	4.2		*

Note: Asterisk (*) in same column of each condition indicates a significant difference ($p < .05$) between the two marked values.

TABLE 9

t TESTS FOR DIFFERENCES BETWEEN REACH AREA MEANS

FOR THE 61-93 HERTZ BAND

Muscle	Condition	Reach Areas	Means
Bicep	Suit	Front	6.0
		Over	2.9
		30° Side	3.1
		60° Side	4.6
	Shirtsleeve	Front	3.8 *
		Over	-3.5 *
		30° Side	0.9
		60° Side	3.4
Trap-ezius	Suit	Front	3.3
		Over	4.5
		30° Side	3.4
		60° Side	2.6
	Shirtsleeve	Front	3.8
		Over	6.2 *
		30° Side	2.0 *
		60° Side	5.9

Note: Asterisk (*) in same column of each condition indicates a significant difference (p .05) between the two marked values.

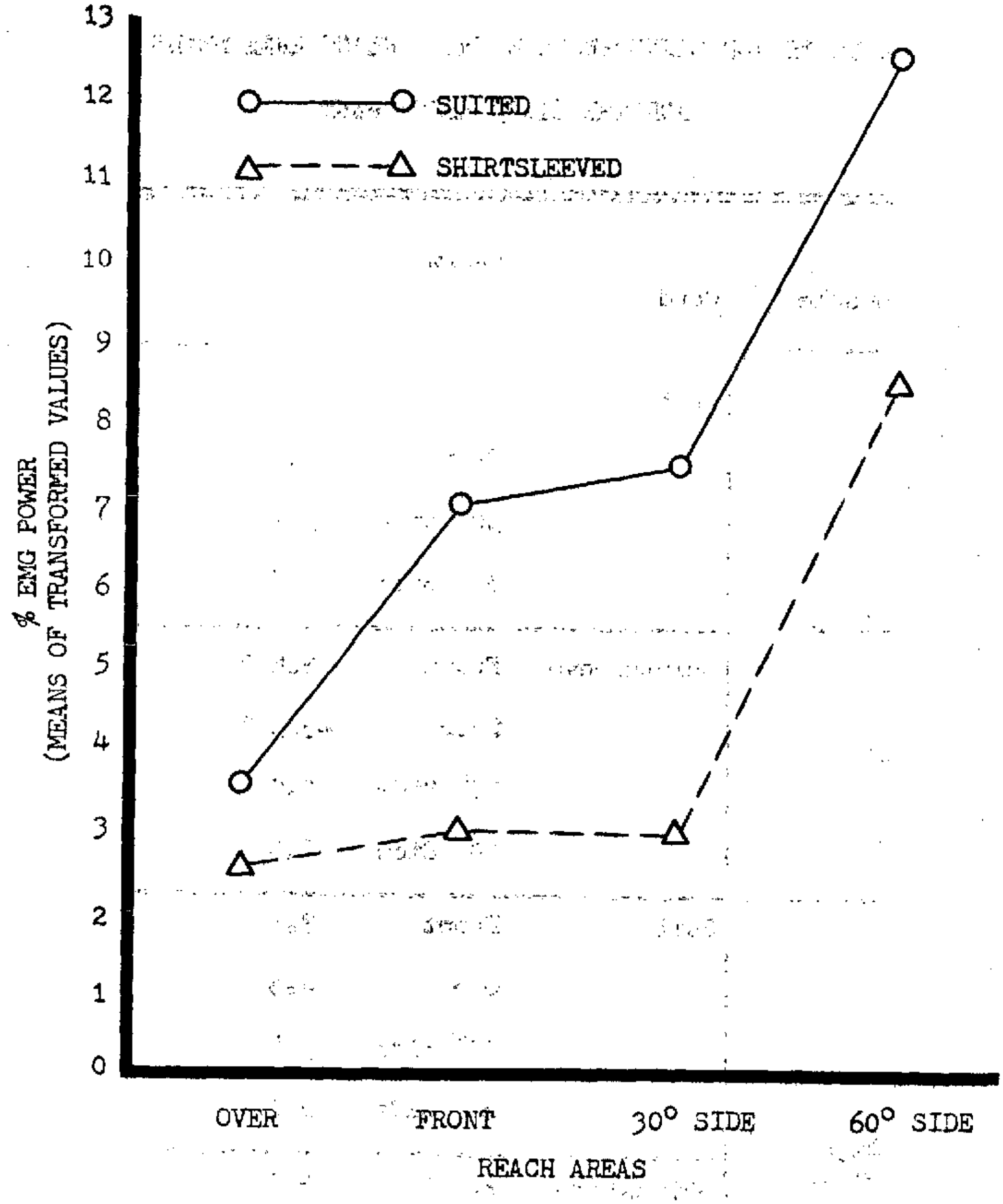


FIGURE 14

MAGNITUDE OF EMG POWER SHIFTS FOR EACH CONDITION

WITH REFERENCE TO REACH AREAS FOR THE

BICEP BRACHII IN THE 10-31 HERTZ BAND

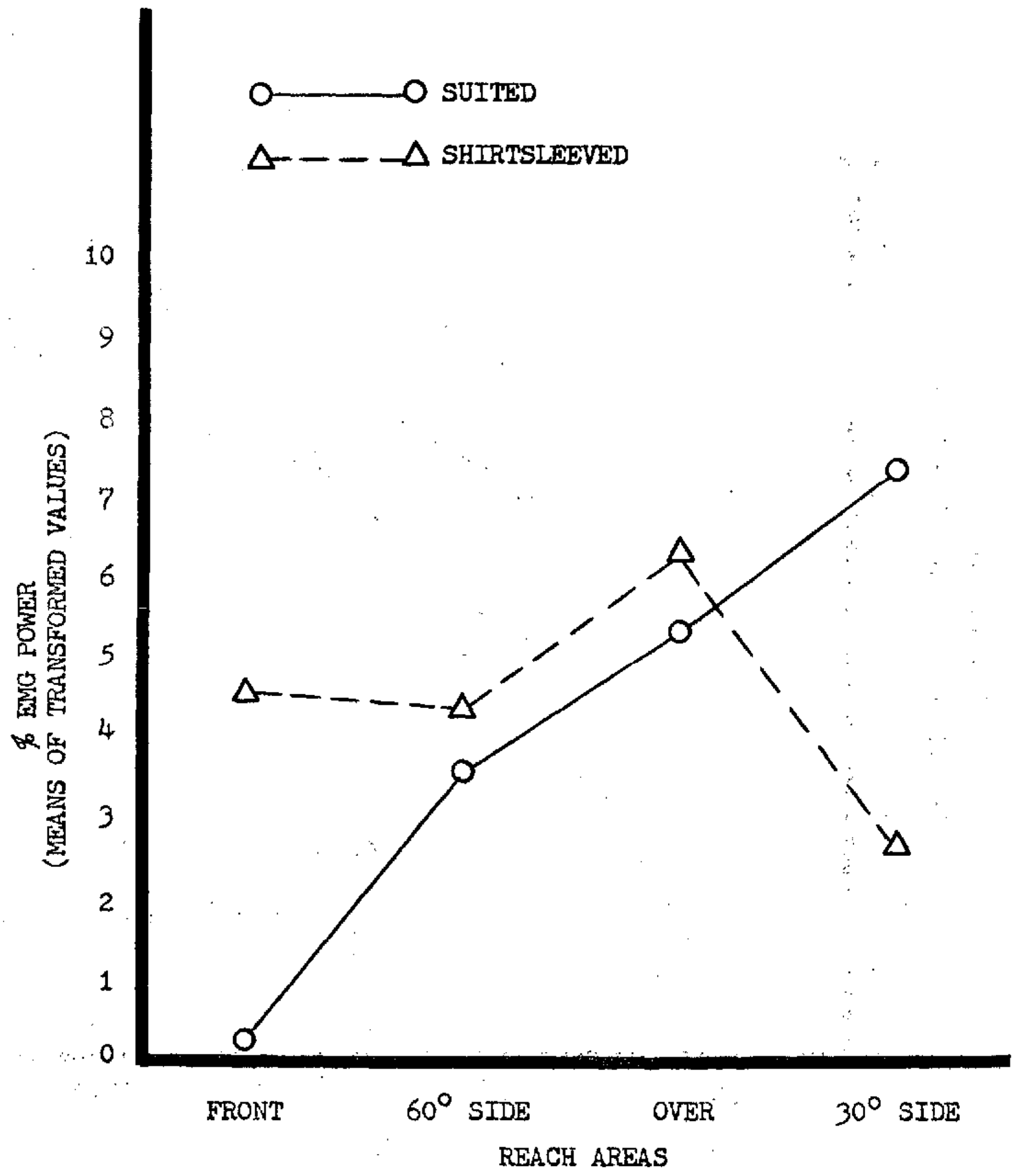


FIGURE 15

MAGNITUDE OF EMG POWER SHIFTS FOR EACH CONDITION WITH REFERENCE TO REACH AREAS FOR THE TRAPEZIUS IN THE 10-31 HERTZ BAND

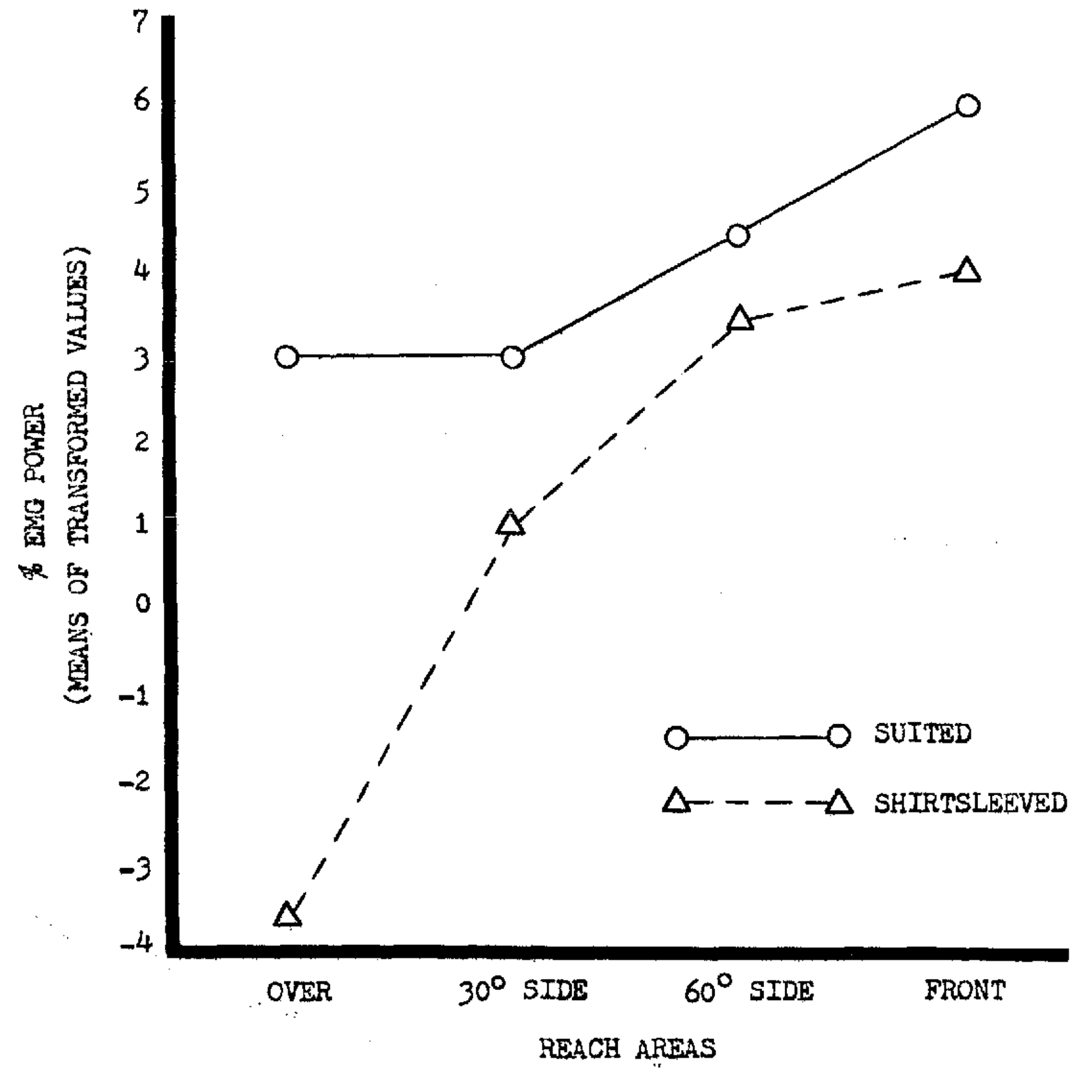


FIGURE 16

MAGNITUDE OF EMG POWER SHIFTS FOR EACH CONDITION WITH REFERENCE TO REACH AREAS FOR THE BICEP BRACHII IN THE 61-93 HERTZ BAND

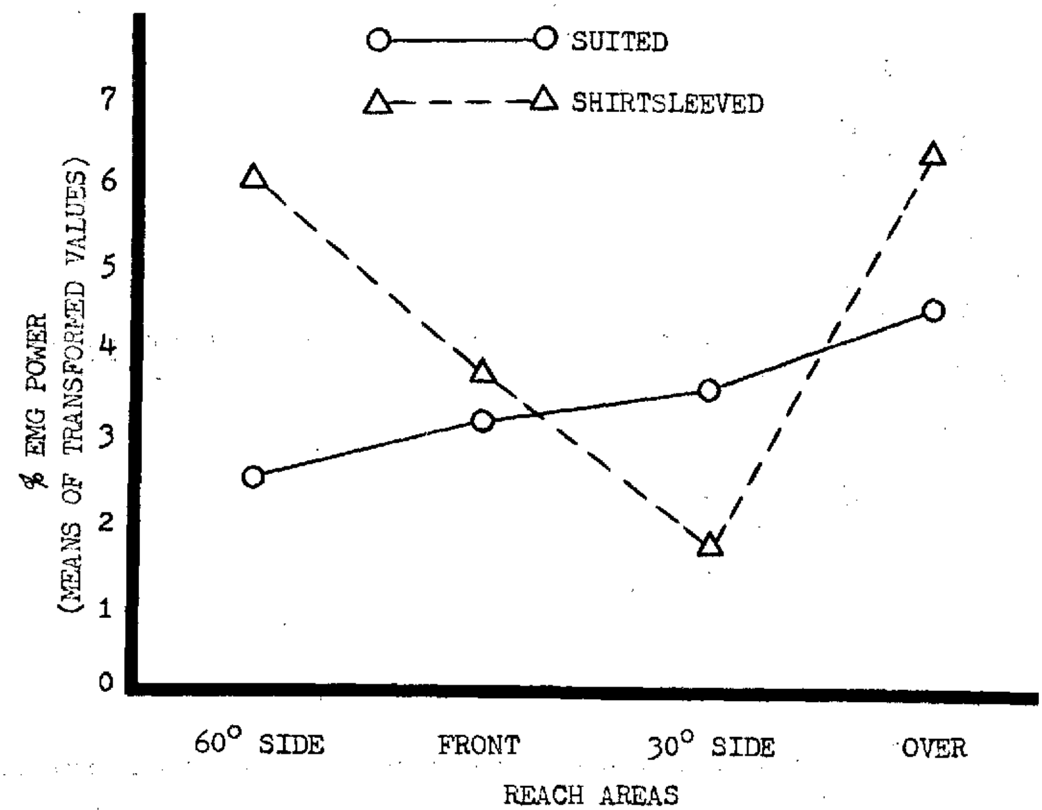


FIGURE 17

MAGNITUDE OF EMG POWER SHIFTS FOR EACH CONDITION WITH REFERENCE TO REACH AREAS FOR THE TRAPEZIUS IN THE 61-93 HERTZ BAND

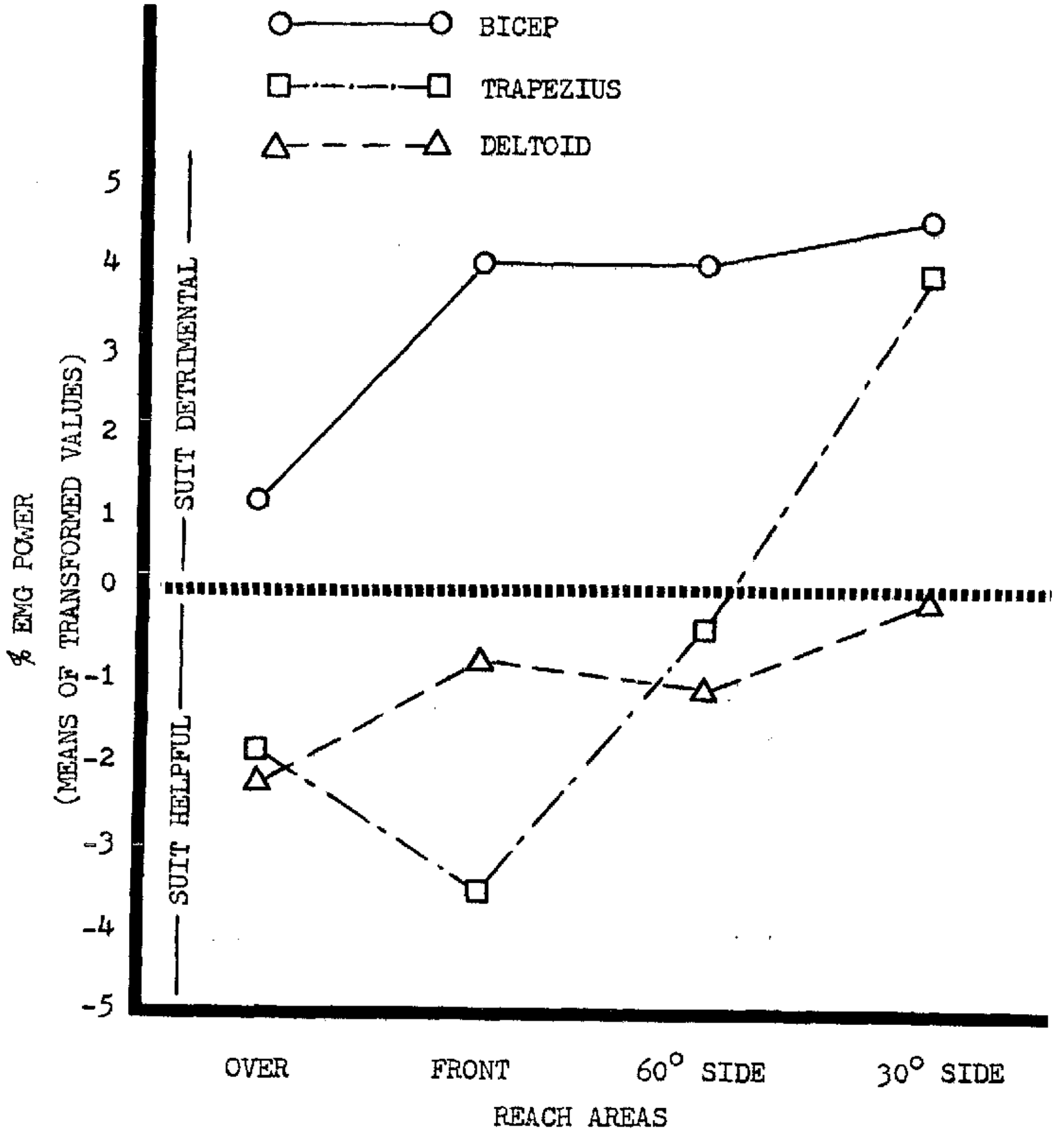


FIGURE 18

MAGNITUDE OF EMG POWER SHIFTS FOR MUSCLE WITH REFERENCE TO REACH AREAS IN THE 10-31 HERTZ BAND. DATA POINTS REPRESENT THE DIFFERENCE BETWEEN THE SUITED AND SHIRT-SLEEVE CONDITIONS FOR THE MUSCLE - REACH AREA COMBINATION

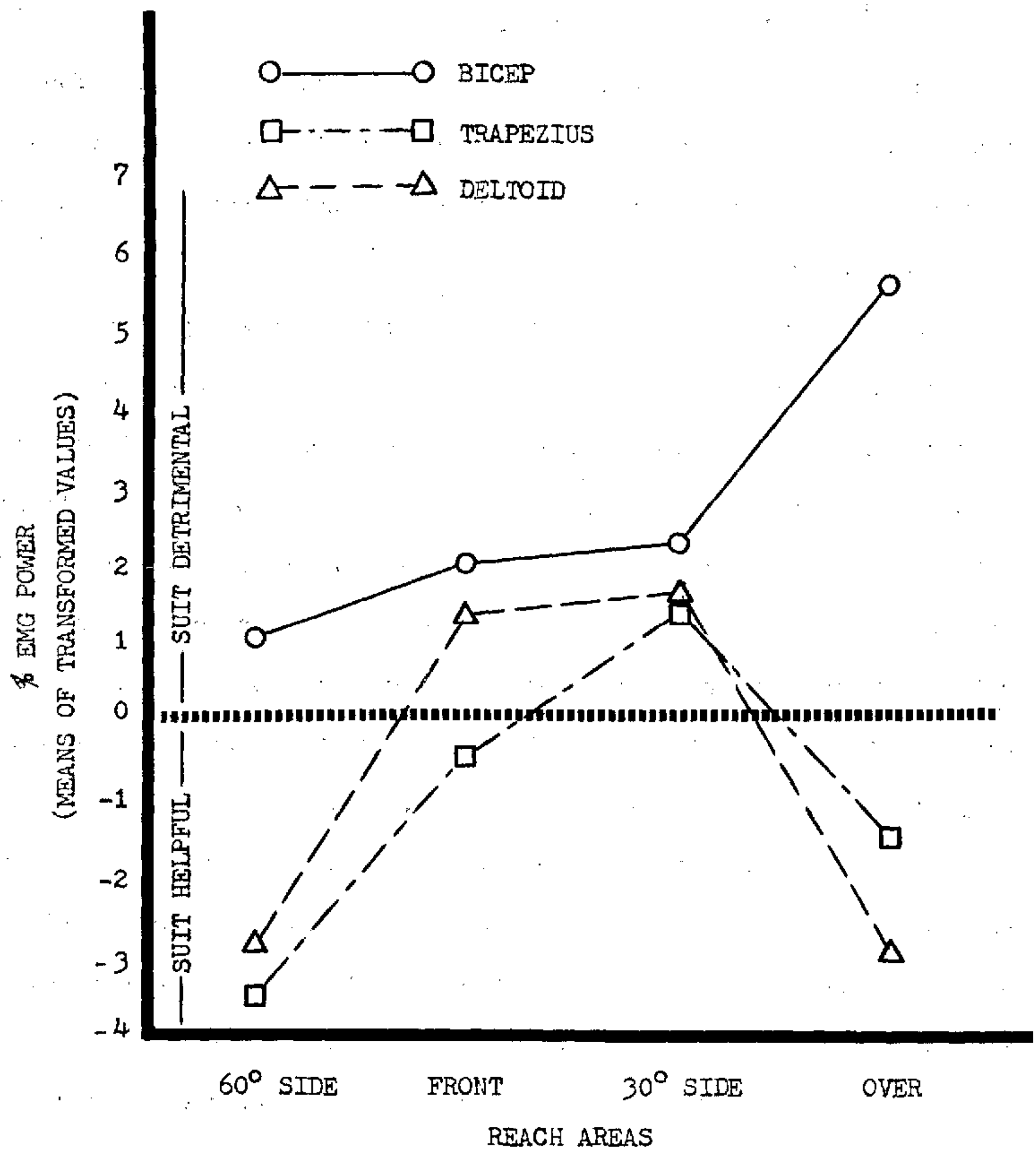


FIGURE 19

MAGNITUDE OF EMG POWER SHIFTS FOR MUSCLE WITH REFERENCE TO REACH AREAS IN THE 61-93 HERTZ BAND. DATA POINTS REPRESENT THE DIFFERENCE BETWEEN THE SUITED AND SHIRT-SLEEVE CONDITIONS FOR THE MUSCLE - REACH AREA COMBINATION

CHAPTER V

DISCUSSION

In an exploratory study such as this, the results are generally taken as suggestive rather than definitive of relationships. The relationships suggested by the results of this study provide some new data, support for existing evidence, and suggest relationships that should be examined further.

The results of this study partially support the hypotheses. First, the spacesuit condition showed a higher mean level of EMG power shift than did the shirtsleeve condition for the bicep muscle, but not for the trapezius or deltoid muscles. Second, reach positions were differentially effective in inducing fatigue related power shifts for the bicep and trapezius muscles, but not for the deltoid. And, there were differences between muscles in their responses to reach positions. Finally, the data support the proposition that the spectral analysis technique is operationally feasible for evaluating muscular fatigue.

Considering the large number of measurements, few statistically significant EMG power shifts were found. This seems to suggest that the subjects were not particularly fatigued at the end of the work sessions in either of the conditions. However, based on physical appearance after the one hour task, and on their comments, the subjects were "tired", especially after a pressurized space suit run. Thus, the work task may have had a more fatiguing effect than is reflected in the number of significant differences, but the fatigue effects were specific to some muscles rather than general to all muscles. The results do suggest a uniqueness in muscle response to the work task: a uniqueness manifested between muscles, but also in the responses of a given muscle to different reach positions. An inspection of the data in Tables 5 and 6 shows that the individual muscles did not respond alike to work sessions. Spearman's rank order correlations (Siegel, 1956) were computed between muscles ranked on reach position means and, in all cases, the coefficients verified that the muscles were different in their response patterns. Moreover, individual muscle data corresponding to the reach positions show that muscles were quite specific in their response to different parts of the work task. This finding, of course, is in keeping with the kinesiologic fact that body member movement is a complex interaction of muscles.

The distribution of significant changes between conditions for each muscle show that the space suit significantly modified some of the muscle responses established by the shirtsleeve condition; however, the direction of change was not always what might be expected from a body encumbering device such as the space suit. Considering both shirtsleeve and space suit conditions for the low frequency band (Table 5), the bicep brachii responded to the space suit condition with increases in EMG power in all reach positions when compared to the shirtsleeve baseline, whereas the trapezius response was a decrease in EMG power for five of the seven reach positions. For the high frequency band, a comparable pattern of effect was evident (Table 6).

The most interesting aspect of these results is the negative responses obtained for the trapezius muscle. Negative responses, i.e., the shirtsleeve responses greater than the space suit responses, indicate that the pressurized space suit altered the shirtsleeve pattern of muscle involvement sufficiently to reduce the effort normally required of the trapezius muscle at some of the reach positions. This means that some features of the space suit made parts of the work task less demanding for the trapezius muscle than did the shirtsleeve condition. This implication is also demonstrated by the consolidated reach data (see Figures 18 and 19). It is important to note that these consolidated data plots show a beneficial space suit effect for the deltoid also.

Whether the pressurized space suit could provide such a performance assist is not a moot question when the functional characteristics of the space suit shoulder joint are considered. To provide as much mechanical assist as possible to physical work in the space suit, designers incorporated a cable assist device into the shoulder joint bellows to provide a stable position when the shoulder extended or abducted to approximately shoulder level or higher. Therefore, when the arm is elevated so high and then relaxed, the shoulder bellows maintains the arm in that position until a force is applied to bring the arm down. The principal reason for incorporating the cable assist was to eliminate the requirement for the suited man to apply continually the upward muscle force needed to counteract the natural tendency of the pressurized shoulder bellows to force the arm down. However, an added benefit, important to this discussion, was derived from the bellows cable assist device: little, if any, antigravity muscle force was required to maintain the arm in an elevated position. The implications of this are readily apparent: the shirtsleeve condition should show more fatigue related EMG power shifts than the space suit at some positions because muscle force was required in the shirtsleeves to counteract gravity and maintain the arm in the elevated positions. Both the trapezius muscle and the deltoid muscle should benefit from this space suit shoulder configuration since both muscles are used to maintain the humerus in elevated positions.

The positive EMG power difference values found for the trapezius muscle at two reach positions (see Table 5) seem to indicate a different work technique was used at these reach positions than at the other reach positions. Arm movement at the 30-30 and 60-30 positions included both shoulder flexion as well as elbow flexion, i.e., the movement was a pumping motion starting with the elbow near the side of the body, thrusting the arm outward along the path dictated by the rod in the reach device, and retracting the arm to the initial position. Whereas, the procedure at reach positions showing negative differences was simply to elevate the arm initially to the plane of the reach position and then flex the elbow to achieve the push-pull action. The "shoulder thrust" procedure not only required the subject to work the bicep by flexing the elbow, but also required him to apply varying amounts of torque with the shoulder muscles to bend the suit shoulder bellows. This, of course, would make the suited task more demanding of the shoulder muscles, including the trapezius and deltoid, than the shirtsleeved task.

An inspection of individual data points supports the proposition that subjects did use different approaches to the push-pull task. It is evident from the range of negative and positive values of the differences between space suit and shirtsleeve conditions for subjects (see Figures 11 and 12) that the subjects were not comparable in their approach to the task. This is borne out by the dichotomized data (see Table 7) where response patterns emerge that tend to confirm a different arm movement technique.

It is obvious from the preceding discussion that the EMG power spectral density analysis has operational feasibility for muscle evaluation. With it, the particular work technique of two of the subjects has been shown to be more demanding of a major muscle group than another work technique, and, therefore, probably less desirable. Little imagination is needed to visualize the application of this method to a host of problems in the areas of time and motion analysis, work performance analysis, work area layout and even procedures analysis.

Although the primary thrust of this study concerned space suited activity, the shirtsleeve data say something about the utility of the spectral analysis technique for evaluating normal work settings. For example, using the data in Table 8, if one considers the bicep muscle only, a design requiring extensive use of the arm in the "over" area seems advisable. But the data for the trapezius muscle argue that such a design would probably exact undesirable penalties on the trapezius. Now, if the data from the two muscles are combined, the results show that work area design should restrict work activities in both the "over" and the "60° side" areas and concentrate activities in the "front" and "30° side" areas. Here, the EMG analysis has provided a bit of validation for a long established human factors principle in work space design. These data also advocate the study of muscle composites rather than single muscles when an experimenter's interest is determining how best to optimize muscle energy or, conversely, to minimize fatigue effects. Just as the physiological functioning of an organism is a complex process which requires a composite of physiological indices to describe it (Malmo, 1959), body motion or movement is a complex interaction of muscles

(Carlsoo, 1972; Cooper and Glassow, 1968), and an appropriate description of the effects of movement may require a composite of the affected muscles.

Chaffin (1969b, 1969c) has drawn the conclusion from his research that separate processes act to cause EMG power shifts in the high and low frequency bands. The data from this study show certain agreements between the two frequency bands, e.g., in Tables 5 and 6, the differences between space suit and shirtsleeve for the bicep are positive in all cases for both frequency bands, and for the trapezius muscle the same reach positions show positive or negative differences, except one. However, some support for Chaffin's position comes from the relationships of EMG power shifts to reach positions. For example, the reach position data for the 10-31 hertz band were arranged to provide an ascending order of EMG power values (see Figure 11), and a straight line appears best to describe the relationship. However, when the 61-93 hertz band data are plotted on the same abscissa of reach positions (see Figure 12), a curvilinear relationship appears appropriate. Also, an inspection of the data in Tables 5 and 6 show that in the low frequency band, the suited condition tends to increase the range of power shifts when compared to the shirtsleeve; however, in the high frequency band, the suited condition tends to narrow the range of power shifts.

The consolidation of the reach positions into four general reach areas was an arbitrary selection based on a subjective appraisal of the work task. However, the results tend to support the efficacy of a more general work task definition. Specific reach areas are shown to be significantly more difficult for certain muscles than for others. Consolidation provides more practical visibility into the potential usefulness of muscle fatigue data in the definition of work space, tasks and procedures. This type of information has applicability to muscle conditioning programs also. Work space design is generally a product of various tradeoffs, and quantitative, reliable information about the muscle fatigue-work place relationship can provide a piece of the tradeoff puzzle not readily available otherwise. For a work area wherein significant use of the arms and shoulders is required for extended periods of time, design considerations can benefit considerably from knowledge about the type, extent, and time history of muscle fatigue for different locations in the work space. This, coupled with the already known effects of arm muscle fatigue on precision motion tasks (Chaffin, 1969b), can provide designers with an important design tool. Concerning muscle conditioning, the idea may seem far-fetched for general application, but in specific task situations where one or two muscles are used primarily and certain factors constrain the design of the work space or task from catering to the muscles in question, or the task if performed infrequently, muscle conditioning may provide a valuable alternative if the muscles and extent of the fatigue are identifiable. In the words of Ricci (1967): "fatigue is inevitable, but well-planned conditioning programs serve to delay its arrival." Certainly, spectral density evaluations can provide valuable information for decisions about the locus and extent of muscle conditioning programs.

In retrospect, the task requirements in this study were not of the fatiguing nature of many studies in the literature designed to exact near maximum muscle contractions for lengthy periods of time. And, this is as it should be for operational purposes where fatigue develops over a period of hours rather than minutes. If an evaluative technique can be shown to provide information useful to the purpose of limiting muscle fatigue and its concomitant effect on both man and his work, then the evaluative technique has practical utility. In this study, the spectral density analysis technique has shown the capability to provide such information.

Future research in this area should be geared to more clearly delineate the muscle/work task relationships using a more homogeneous composite of muscles and a highly representative task determined from the kinematic analysis of appropriate work situations. With an appropriately developed taxonomy of muscle/task element/fatigue data and in-line computer analysis of the spectral aspects of the data, the designer and time-and-motion technologist is provided a real-time muscular fatigue prediction capability.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The power spectral density analysis of EMG recordings from the bicep brachii, middle deltoideus, and upper trapezius of the right torso from four subjects performing a push-pull task at various reach positions in the right reach envelope in a space suit and in shirtsleeves revealed reliable differences between muscles in fatigue-induced responses to individual reach positions, and a differential sensitivity in responses of individual muscles to the various reach positions in the reach envelope.

In the pressurized space suit, the bicep brachii was most affected by the encumbrance. Considering the differences in EMG power between the space suited condition and the shirtsleeve baseline, the bicep brachii registered an increase in power in both the 10-31 hertz band and 61-93 hertz band at all seven reach positions as a result of 1 1/2 minutes of work. However, the trapezius muscle showed a decrease in EMG power at several of the reach positions (as did the deltoideus), indicating a beneficial rather than detrimental effect from the pressurized space suit. This paradoxical finding resulted from a peculiar characteristic of the space suit design which minimizes the muscular effort required to hold the arm in positions above shoulder level. For the positions in which the trapezius muscle registered an increase in EMG power, as opposed to the positions mentioned above, a different approach to the task by the subjects was judged to have caused the difference. Important to this finding is the fact that the spectral analysis method verified the consequences of a minor task procedural difference among the subjects that was observed during the performance of the task.

A graphical comparison of the EMG data from two frequency bands, the

10-31 hertz band and the 61-93 hertz band, showed what appeared to be a difference in the distributions of the data. When the 10-31 hertz band data were plotted on reach positions to show a linear trend, the 61-93 hertz band data plotted on the same abscissa showed a curvilinear trend. This apparent difference in the distributions of data in the two frequency bands lends support to Chaffin's (1969) conclusion that separate processes are responsible for the EMG power shifts in the two frequency bands.

A consolidation of the data into more general reach areas, i.e., four reach areas versus the seven reach positions, was attempted to determine if this would provide more useable data for work place and task design purposes. The consolidation of the data into general reach areas did provide more practical visibility into the potential usefulness of the muscle fatigue data in the definition of work space, tasks, procedures, and even muscle conditioning programs.

The task requirements of this study were not of the fatiguing nature of many studies in the literature designed to exact near maximum muscle contractions during test periods. And, this is as it should be for operational purposes where fatigue may develop over a period of hours rather than minutes. The absence of an overly demanding task may have been instrumental to the finding of few statistically significant EMG power shifts, i.e., the subject's muscles were not sufficiently fatigued to show significant shifts. However, the data also suggest that the relationship of muscles to reach positions may have had a significant effect on the absolute number of significances. The results suggest a uniqueness of muscles in their responses to the work task. Muscles are shown to be different in their response patterns to reach positions. Moreover, the data indicate that the individual muscles were rather specific in their responses to different reach positions.

Based on the results of this study, several conclusions can be drawn. Specific to this study, it is concluded that:

1) The pressurized space suit provided a more fatigue-inducing work environment than did the shirtsleeve baseline for the bicep brachii, but less demanding of the deltoideus and trapezius because of a peculiar design characteristic of the space suit.
2) The pressurized space suit changed the pattern of normal shirtsleeve muscle fatigue responses for all muscles.
3) The three muscles showed inter-muscle differences to the reach positions that each responded to maximally.
4) Individual muscles showed differential sensitivity to the seven reach positions, i.e., certain reach positions imposed more fatigue related shifts in EMG power than did others.
5) Differences in the way a subject performs a task involving arm movement may alter the fatigue related EMG power shifts.
6) Consolidating data into more general reach areas provided more visibility into the practical applications of the data for design of work places and tasks.
7) Frequency analysis is a valuable tool for analyzing fatigue producing muscular performance.

In addition, the following general conclusions are made:

1) The power spectral density analysis can provide reliable EMG data useful for many practical industrial applications where muscular fatigue accumulates gradually over a period of hours.

2) Future research in this area should be geared to more clearly define the muscle/work task relationships using a more homogeneous composite of muscles and a highly representative task determined from the kinematic analysis of appropriate work situations. With an appropriately developed taxonomy of muscle/task element/fatigue data and in-line computer analysis of the spectral aspects of the data, the designer and time-and-motion technologist is provided a real-time muscular fatigue prediction capability.

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APPENDIX A

TESTING PROCEDURE

SUBJECT________________ DATE________________

CONDITION________________ TIME________________

Time	Data Procedure	Time	Task Procedure
:00	Begin isometric measure	:00	Set arm weight
:20	End isometric	:20	Remove arm weight
:30	Begin dynamic measure	:30	Begin work session
:50	End dynamic measure		
1:40	Begin dynamic measure		
2:00	End dynamic measure	2:00	End work session
2:10	Begin isometric measure	2:10	Set arm weight
2:30	End isometric	2:30	Remove arm weight Begin rest period
	Tape recorder OFF		Set next reach position
	Tape recorder ON		
4:00	Begin isometric measure	4:00	End rest period Set arm weight
	Repeat cycle		Repeat cycle

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