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ELECTROMYOGRAPHIC ANALYSIS OF SKELETAL MUSCLE CHANGES ARISING FROM 9 DAYS OF WEIGHTLESSNESS IN THE APOLLO-SOYUZ SPACE MISSION

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16. Abstract

The purpose of this investigation was to evaluate changes in skeletal muscle function that might occur within 10 days of weightlessness. Of particular interest were changes in excitability, electrical efficiency, and fatigability. Both integration and frequency analyses of the electromyograms from voluntary contractions were performed in one crewman of the Apollo-Soyuz Test Project mission. As a result of 9 days of weightlessness, muscle excitability was shown to increase; muscle electrical efficiency was found to decrease in calf muscles and to increase in arm muscles; and fatigability was found to increase significantly, as shown by spectral power shifts into lower frequencies. It was concluded from this study that skeletal muscles are affected by the disuse of weightlessness early in the period of weightlessness, antigravity muscles seem most affected by weightlessness, and exercise may abrogate the weightlessness effect. It was further concluded that electromyography is a sensitive tool for measuring spaceflight muscle effects.

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ELECTROMYOGRAPHIC ANALYSIS OF SKELETAL MUSCLE CHANGES ARISING FROM 9 DAYS OF WEIGHTLESSNESS IN THE APOLLO-SOYUZ SPACE MISSION

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SUMMARY

The objective of this study was to assess skeletal muscle changes that might occur during a period of weightlessness of less than 10 days. The U.S. crewmembers of the Apollo-Soyuz Test Project were the subjects for this investigation. Using an electromyogram, the gastrocnemius, soleus, biceps brachii, and brachioradialis muscles were evaluated for excitability, electrical efficiency, and fatigability, using both integration and frequency analyses.

Findings indicated that disuse effects of weightlessness on skeletal muscles are precipitated very early in the period of weightlessness and gradually increase in severity as the weightlessness continues. Also, the antigravity muscles appear to be affected most by weightlessness. Skeletal muscle excitability (i.e., frequency of firing) was increased as evidenced by significant shifts of predominant electrical activity into higher frequencies. Muscle electrical efficiency, as measured by the ratio of muscle force to electrical activity, decreased in the gastrocnemius but increased in the biceps brachii after 9 days of weightlessness. Fatigability, as evidenced by shifts of spectral power into lower frequencies, increased as a result of the period of weightlessness.

INTRODUCTION

The Skylab Program afforded the first opportunity to study the effects of long-duration weightlessness on human skeletal muscle function. The results of the Skylab assessments provided ample evidence that normal muscle function is significantly altered by periods of weightlessness of 59 days or more. This conclusion is supported by several physiological and biochemical changes that occurred during the Skylab missions (ref. 1); these changes have been shown by ground-based laboratory studies to be related to abnormal muscle function (refs. 2 to 7). For example, in the Skylab crewmen, a decrease

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*Technology, Incorporated.

in tension capability after flight suggested the possibility of muscle atrophy. The spectral characteristics of the electromyograms indicated states of muscle superexcitability and increased fatigability that only gradually returned to baseline values (ref. 8). Losses in body calcium and potassium also occurred, as well as alterations in enzymes related to muscle function. According to laboratory studies, the minerals and enzymes that changed in the Skylab crewmen are instrumental to neuromuscular transmission and muscle function efficiency (refs. 9 to 11).

Many laboratory studies have been made to determine the effects of disuse on skeletal muscles. The results of muscle immobilization studies have been varied and sometimes inconsistent. A principal reason for this inconsistency is the relative ineffectiveness of the immobilization techniques (e.g., joint pinning, plaster cast encasement, etc.) for achieving near-absolute disuse conditions without concomitant confounding by the force of gravity. Likewise, disuse studies predicated on nerve cutting and tendon severing are not effective because the severe trauma inflicted on the neuromuscular system may transcend and confound the true effects of muscle disuse (refs. 3, 6, and 12 to 14).

Muscle function is appropriately described by the characteristics of its electrical activity, and the measurement of muscle electrical activity is called electromyography (EMG). Electromyography has been used for many years to study muscle condition, especially muscle fatigue (ref. 15). The integrated EMG (IEMG) has been used most frequently for analyzing muscle function because it is an amalgamation of simultaneous variations in amplitude and frequency and is a convenient way of evaluating muscle electrical data (ref. 15).

The first useful information produced by the integration technique resulted from the work of Bigland and Lippold (ref. 16). They found that a linear relationship exists between the level of muscle activity and the strength of voluntary muscle contractions, and several subsequent studies have substantiated that finding (refs. 17 to 19).

In a further refinement of the integration technique, DeVries (ref. 20) evaluated the functional state of muscle in terms of the "efficiency of electrical activity" (EEA). The EEA is simply the IEMG plotted as a function of the force of isometric contraction with the slope of the regression line indicating the EEA. DeVries found the measurement technique to be useful as a physiological approach to the evaluation of muscle quality.

The use of frequency analysis for the evaluation of muscle activity is more recent and provides a unique method for studying muscle fatigue. Using this technique, Chaffin (refs. 21 and 22) has demonstrated that, as a muscle progressively fatigues, the spectral density shifts from higher (40- to 70-hertz band) to lower (30 hertz and below) frequencies. With isometric and repetitive sequence tension on the biceps brachii of both pathologically symptomatic and asymptomatic individuals, Chaffin found that, in the case of most common myopathies, the EMG spectra are shifted toward higher frequencies when compared to asymptomatic individuals. Increased amplitudes were especially pronounced in the 100- to 200-hertz band. Using needle electrodes, Walton (ref. 23) and Gersten et al. (ref. 24) also found that muscle abnormalities of many forms could be detected by shifts of the predominant frequency into the higher bands.

In another study,[1] Chaffin found that amplitude shifts to the lower frequencies were coincidental with subjective muscle discomfort ratings, decreased psychomotor coordination, and increased muscle tremor. Chaffin concluded that EMG spectra are objective measures of muscle condition and performance and are directly relatable to human performance and behavior.

The objective of the study discussed in this report was to continue the space-flight evaluation of skeletal muscle function that began in the second manned Skylab mission. The purpose was to investigate changes in skeletal muscle electrical activity that occur after short-term weightlessness (i.e., less than 10 days). The following changes were hypothesized: (1) heightened excitability as evidenced by a shifting of the predominant spectral power into higher frequencies, (2) reduced muscle electrical efficiency, and (3) increased muscle fatigability when the muscles are subjected to a moderate fatigue-inducing stress.

The authors wish to express their sincere appreciation to Dr. George W. Hoffler, NASA Lyndon B. Johnson Space Center, for his influence, support, and guidance during the planning and conducting of this study. Sincere appreciation is also extended to Joseph Baker and John Donaldson, Technology, Incorporated, for their most able assistance in the preparation of hardware and the collection of data.

As an aid to the reader, where necessary the original units of measure have been converted to the equivalent value in the Systême International d'Unités (SI). The SI units are written first, and the original units are written parenthetically thereafter.

METHODS

Instrumentation

A skeletal muscle stress apparatus was designed and built for controlled isometric muscle testing. The device was adjustable to accommodate the 5th to 95th percentile person, anthropometrically, and permitted measurement of the force exerted by the subject's arm or leg. A force transducer was mounted on the stress apparatus. Calibration of the force signal was accomplished by coupling a known amount of weight to the transducer. A small meter provided feedback of force levels to the subject.

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[1] D. B. Chaffin, "EMG Research for Industrial Applications," unpublished interim report, Univ. of Michigan, 1969.

A two-channel EMG detector was built using differential amplifiers. The output of each differential amplifier was passed through an active 5-hertz high-pass filter to remove direct-current (dc) offset or movement artifacts from the data. An internally generated calibration signal was provided by a nominal 20-hertz, 350-microvolt root-mean-square (rms) sine wave, which could be switched to the input of the differential amplifiers.

Muscle force was measured using a universal transducing cell coupled with a load cell accessory (range 0 to 890 newtons (0 to 200 pounds)) and a bridge amplifier. An additional stage of gain was added so that the output from the bridge amplifier could be optionally increased when measuring low force levels.

All data were recorded at a speed of 9.53 cm/sec (3.75 in/sec) on magnetic tape by a four-channel instrumentation recorder (two channels of EMG signals, one channel of force signal, and one channel of interrange instrumentation group (IRIG) B time code. A four-channel strip-chart recorder was used to monitor the data playback from the magnetic tape during the experiment. Figure 1 is a diagram of the instrumentation.

Protocol

Data were taken 45, 30, and 15 days before the flight (F-45, F-30, and F-15). For each crewman, two muscles on the lower leg, the gastrocnemius and the soleus, and two muscles on the arm, the biceps brachii and the brachioradialis, were instrumented. Surface electrodes, 1.12 centimeters (0.44 inch) in diameter, were used with space-flight-type electrode paste. Figure 2 shows the electrode positions. The electrodes were applied approximately 1 hour before testing, and care was taken to reproduce electrode positions accurately from one test to the next.

The crewman was seated in the muscle stress apparatus, and the device was adjusted for leg stress measurements. On F-45 only, the crewmen performed an initial series of three instantaneous maximum voluntary contractions. The maximum voluntary contraction (MVC) found for each crewman was used to determine his force levels for the remainder of the experiments. The crewman then exerted a series of graded force levels as follows:

10 seconds at 10 percent MVC - 20 seconds rest
10 seconds at 20 percent MVC - 20 seconds rest
10 seconds at 30 percent MVC - 20 seconds rest
60 seconds at 50 percent MVC

The muscle stress apparatus was reset for testing the arm muscles. The procedure was identical to that for the leg except the 60-second effort was at 40 percent MVC. The 60-second constant-hold test was used to evaluate the fatigability of the four muscles. On F-30 and F-15, a single MVC was taken after the completion of the arm and leg protocols. On recovery day, the procedure was the same as that on F-30 and F-15.

Data Processing

The analog force and EMG signals were digitized for processing. The analog force signal was low-pass filtered at 10 hertz and sampled at 20 samples/sec. A 400-hertz upper frequency limit was selected for EMG power spectral density (PSD) analysis. Consequently, the analog EMG data were low-pass filtered at 400 hertz and digitized at 1000 samples/sec (ref. 25).

The computer program EMGAN was written to process the force and EMG data (ref. 26). Force data were calibrated into pounds and averaged over 1-second intervals. The EMG signals were analyzed in 4-second segments. The data were calibrated into microvolts, and the integrated value for each segment was found.

A cosine taper was applied to the first and last tenths of each data segment (for leakage reduction (ref. 27)), the discrete Fourier transform was taken, and the magnitude of the PSD was calculated. To reduce random error, the PSD was smoothed over approximately 10-hertz intervals.

RESULTS

Because of toxic gas infiltration into the Apollo command module crew cabin during descent to Earth and the resulting concern for the health of the crewmen, postrecovery electromyographic data were collected on only one crewman. The problems in generalizing the results of data from one subject to a larger population are apparent. Nevertheless, one-of-a-kind space-flight data should not be ignored simply because there is a problem with the universality as long as care is exercised in generalizing the results. Practical application must adhere to representativeness.

Muscle Excitability

Skeletal muscle disuse attributable to 9 days of space-flight weightlessness resulted in increased excitability of the instrumented muscles of this study. Figures 3(a) and 3(b) show the preflight and postflight distributions of spectral power for the gastrocnemius and biceps brachii. These data indicate that each muscle had an increased predominant firing frequency and the tendency for the distribution of the power spectrum to be shifted toward the higher frequencies. The increase in firing frequency was approximately 30 hertz (25 percent) and 20 hertz (40 percent), respectively.

The t-test for related measures was used to determine whether the spectral power changes that appear to be associated with the shifts in predominant frequency (figs. 3(a) and 3(b)) were statistically significant. The results are given in table I. The hypothesized decrease in spectral power in the low-frequency band was significant for the gastrocnemius only, whereas the power increase in high-frequency response was significant for the biceps only.

The soleus muscle (fig. 3(c)) showed a postflight increase in predominant firing frequency of approximately 30 hertz, or 25 percent. In the band from 40 to 150 hertz, there was a significant decrease in spectral power ($t = 3.25$, $p < 0.02$), which corresponded to the shift in the predominant frequency from approximately 125 to 155 hertz following the 9 days of weightlessness. However, as in the gastrocnemius, a consistent pattern of spectral power increase in the higher frequencies was not found.

The brachioradialis muscle showed the least excitability effects from the weightlessness. There was no shifting of predominant frequency from the level of the preflight baseline and no consistent pattern of change in either the low- or the high-frequency band.

Muscle Electrical Efficiency

The electrical efficiency of a muscle is defined as the reciprocal of the ratio of IEMG to pounds force. Because the level of force maintained for a particular postflight trial varied from that maintained before flight, the data were cast to reflect the muscle electrical efficiency, i.e., microvolt-seconds per pound of force, for each of the four submaximal MVC trials. These data are plotted in figures 4(a) to 4(d). The t-test for related measures was used to evaluate differences in the IEMG levels. After flight, the biceps brachii and the brachioradialis exhibited significantly higher levels of electrical efficiency ($t = 4.33$, $p < 0.05$; and $t = 8.33$, $p < 0.01$, respectively); the gastrocnemius showed a significantly lower level of electrical efficiency ($t = -3.58$, $p < 0.05$); and the soleus exhibited mixed effects.

The preflignt and postflight IEMG levels generated by the muscles during the 1-minute fatigue-inducing stress were also cast to reflect muscle electrical efficiency. These data are shown in figures 5(a) to 5(d). The biceps and brachioradialis showed higher levels of electrical efficiency after flight and the tendency to decrease in electrical efficiency as fatigue progressed, both after flight and before flight (figs. 5(c) and 5(d)). The gastrocnemius also showed the tendency to decrease in electrical efficiency as tension was maintained, but the postflight level of electrical efficiency was less than the preflight level (fig. 5(a)). The soleus muscle showed an interaction effect between muscle electrical efficiency and the time course of the isometric stress (fig. 5(b)).

Muscle Fatigability

Analyses of variance were conducted on the power spectral data of the four muscles used in this study. Three main effects were considered in the analyses: (1) conditions (preflight and postflight), (2) time increments (i.e., the time intervals at the beginning and end of the 1-minute continuous isometric hold for which the EMG was spectrally analyzed), and (3) frequency bands. The frequency bands used for the analysis of the muscle data were 10 to 60 hertz, in 10-hertz increments, for the leg muscles and 10 to 30 hertz, in 10-hertz increments, for the arm muscles. The band ranges were arbitrarily chosen contingent on the location of the predominant frequency band of the muscle. The predominant frequency for the two leg muscles was considerably higher than that for the arm muscles; therefore, a wider band was used in the analysis. Summaries of the analyses of variance are given in table II.

In the calf muscles, there was a significant difference between the preflight and postflight spectral power levels. The postflight data indicated a significantly greater progressive power shift into the lower frequencies as a result of the 1-minute isometric stress. Figures 6(a) and 6(b) are plots of the power spectral data from the gastrocnemius muscle. Figure 6(a) shows the extent of the preflight downward shift resulting from the 1-minute continuous hold at 50 percent MVC, and figure 6(b) shows the postflight data. More dramatic shifts of the spectral power into the lower frequencies are evident in the postflight data ($t = 5.53$, $p < 0.01$). Figures 7(a) and 7(b) show the differential effect of the space-flight weightlessness on the biceps brachii. Preflight shifts appear principally in the low frequencies (30 hertz and below) with smaller change evidenced in the higher frequencies. During the postflight period, there was an increase in low-frequency power but a significant decrease of the spectral power in the higher frequencies of 60 to 100 hertz ($t = 3.83$, $p < 0.01$).

DISCUSSION

Previous research has demonstrated that marked changes occur in skeletal muscle function after a prolonged period (59 days) of space-flight weightlessness (ref. 8). The changes were manifested in an antigravity muscle of the leg, the gastrocnemius, and consisted of muscle superexcitability and heightened fatigability.

The present investigation of skeletal muscle function involving both leg extensor and arm flexor muscles in a shorter period of weightlessness (9 days) has shown that the muscle dysfunction characteristics prominent after 59 days of weightlessness (the second manned Skylab mission) are also evident after only 9 days of weightlessness (the Apollo-Soyuz Test Project (ASTP) mission).

Although it is unwise to make deductions based on a single case, it appears from the data of this study that the short period of weightlessness (9 days) in the ASTP mission brought about skeletal muscle changes that occurred previously in longer durations of weightlessness.

As was hypothesized for this study, the 9 days of weightlessness resulted in increased excitability of both the upper and lower torso skeletal muscles. Although the changes in excitability were not as pronounced as in the longer-duration Skylab mission, they nevertheless suggest that the skeletal muscles of the crewman were affected by the relatively short period of weightlessness. The changes in excitability of the upper and lower torso muscles indicate that skeletal muscles are susceptible to functional changes associated with the reduced muscle activity in weightlessness. Because all changes were in the direction of greater sensitivity, i.e., higher firing rates in response to a specified contraction force, the effect was probably at the muscle fiber level. Previous clinical studies have indicated that random loss or reduced activity in muscle fibers, as in myopathy, results in higher firing frequencies of the muscle, whereas dysfunctions of neural loci result in lower firing frequencies (refs. 23, 24, and 28 to 30).

Several studies have provided evidence that the electrical activity of muscles increases as a function of tension (refs. 16 and 31 to 34). The results of this study concur with those findings because all four of the muscles demonstrated an increasing IEMG with increasing force of contraction. Also, previous studies have shown that, after a period of immobilization or disuse, or, as in myopathy, the amplitudes of muscle EMG's are depressed when compared with EMG's acquired before disuse (refs. 23 and 35). Again, the results of this study are in general agreement, although some muscles (e.g., the gastrocnemius) are capable of responding with increased rather than decreased amplitudes. Because muscle disuse is associated with increased firing frequencies (refs. 8, 36, and 37), increased firing frequencies with lowered thresholds and smaller motor units (refs. 10, 38, and 39) and smaller motor units with smaller amplitudes (ref. 38), it is reasonable to expect decreased EMG amplitudes to be associated with muscle disuse. The greater amplitudes produced by the gastrocnemius in response to disuse are not fully understood; however, existing evidence suggests that this finding is not anomalous. For example, Liberson et al. (ref. 40) have provided indirect evidence that the IEMG of the gastrocnemius may show an inverse relationship to force of contraction, the highest tensions showing the lowest levels of electrogenesis.

Muscle electrical efficiency, as applied by DeVries (ref. 20), appears to describe adequately the efficiency or quality of muscle activity under normal gravity conditions. Figure 4 shows that the biceps brachii and brachioradialis are almost equally efficient during the flexing of the lower arm; but, in ankle extension, the soleus appears to be more efficient than the gastrocnemius. However, the soleus, a "slow-twitch" postural muscle, is suited for endurance and thus would be expected to be more efficient than the "fast" gastrocnemius. The preflight soleus (fig. 5) appears to improve in electrical efficiency with time as a 50-percent MVC is maintained for 1 minute. This improved efficiency is inconsistent with established relationships in muscles that show that increasing amplitudes, and therefore decreasing electrical efficiencies, are associated with constant tension that is maintained during a period of time (refs. 16 and 34). However, other studies have shown that the human calf muscles do respond initially in an uncharacteristic manner to a constant tension. Lippold et al. (ref. 34) found that, for tensions between 10 and 80 percent of the MVC, the IEMG level of the gastrocnemius decreased slightly during the first minute or 2 before beginning an upward trend. Edwards et al. (ref. 31) found comparable results for the soleus muscle. Muscle tension in this study was maintained for only 1 minute, and both the gastrocnemius and soleus did exhibit an initial decrease in their IEMG levels, with the soleus showing the larger and more lengthy decrease.

Previous research has shown that the soleus is highly affected by tenotomy (tendon cutting), which renders the muscle incapable of contraction. These studies have shown that lack of activity tends to convert the soleus into a fast-twitch muscle (refs. 41 to 43). Although tenotomy is much more traumatic and reduces motor activity in a muscle to a greater extent than does simple disuse (ref. 14), it was still anticipated that the soleus might show a greater effect from weightlessness than the gastrocnemius. This anticipation was tentatively confirmed by the results of the 1-minute, constant-hold stress. The slope coefficients shown in figure 5(b) suggest a greater rate of change in the soleus electrical efficiency after weightlessness than in the gastrocnemius; however, insufficient data precluded statistical verification. A greater effect of weightlessness on the soleus is further supported by the results of the analysis of variance of the spectral power, wherein the soleus shows a greater degree of significance. (See the subsection entitled "Muscle Electrical Efficiency" and table II.)

The interpretation of the results of muscle activity in terms of the muscle electrical efficiency concept is less clear after a period of weightlessness than before weightlessness. For example, the increased electrical efficiency shown in the arm muscles after flight is surprising because all the muscles were expected to show some degree of deficiency. A possible explanation for this disparity may be found in the quantity and quality of exercise received by the arm muscles during flight. The in-flight exerciser used during the ASTP mission was generally more amenable to upper torso exercise, although leg exercises could be performed. Thus, the arm muscles may have received disproportionately more exercise. This possibility, together with the short mission duration, the greater use of arms than legs in normal mission operations, and the added possibility that the arm muscles are less affected by the absence of gravity than the antigravity muscles, could account for postflight efficiency enhancement in the arm muscles, especially if the frequency and intensity of arm exercises were greater during flight than before flight.

Another possible explanation for the observed results is that the increased muscle electrical efficiency is an artifact resulting from differences between postflight and preflight IEMG levels. In this study, the biceps and brachioradialis both had depressed IEMG levels after flight; this finding is supported by other muscle studies that have shown smaller EMG amplitudes associated with muscle dysfunctions attributable to either pathological states or muscle immobilization (refs. 23 and 35). Thus, the smaller postflight EMG amplitudes from comparable preflight and postflight force levels would necessarily produce smaller IEMG per unit force ratios for the postflight data and, therefore, reflect better efficiency.

Possibly, the lower postflight IEMG's reflect better efficiency because approximately the same tension was attained after and before flight with a lower level of muscle electrical activity. Unfortunately, this argument cannot be tested directly from data in this study because the exercise parameter was not manipulated during flight. Also, EMG data using the controlled procedures of this study do not exist for longer periods of weightlessness. However, the relationship between muscle electrical efficiency and muscle fatigue, as reflected by changes in the spectral power content of the lower frequency bands during the 1-minute stress, makes the validity of the argument dubious because greater rates and ranges of muscle fatigue occurred after flight whether muscle electrical efficiency was better or worse. Figures 8(a) and

8(b) show the data for the gastrocnemius and biceps muscles, respectively, wherein the spectral power index of fatigue is plotted against muscle electrical efficiency. For the gastrocnemius, the preflight level of electrical efficiency is greater than the postflight level, and the lower efficiency after flight is associated with a greater range and rate of fatigue. For the biceps brachii, the postflight level of electrical efficiency is greater, but instead of the postflight range and rate of fatigue being smaller, as might be expected, it is greater. Thus, the fatigue associated with the change in electrical efficiency during muscle stress after flight is greater than before flight, even though the level of postflight electrical efficiency was greater. This implies that the increased electrical efficiency of the biceps brachii was obtained at the cost of greater fatigability. Yet, it seems more correct to expect that the electrical efficiency is the dominant factor and that increased electrical efficiency in the muscle would be associated with decreased fatigability.

That short-term exposure to weightlessness heightens fatigability in skeletal muscle is readily demonstrated by the results of this study. Significantly greater amounts of spectral power developed in the lower frequencies after the period of weightlessness than before in response to the fatigue-inducing stress. These data suggest that the disuse associated with weightlessness temporally facilitated certain muscle conditions, as evidenced by a degree of supersensitivity, which led to quickened fatigability and the earlier incidence of synchronous discharges and recruitment of higher threshold motor units.

Although it is obvious that the period of weightlessness heightened postflight skeletal muscle fatigability, the exact cause is not readily obvious. A simplistic approach is to assume that the lowered threshold, more highly excitable muscle fibers, which fire at higher rates in response to a given tension, are more easily fatigued. It is generally agreed that the stronger the contraction of a muscle, the higher its discharge frequency until fatigue develops. This suggests that the contraction of a muscle that has been subjected to disuse is stronger or more intense for a given force than the same contraction before the period of disuse. For example, dystrophic muscle fibers cannot produce as much tension as normal fibers; therefore, more fibers are used for a given tension, which implies that a greater proportion of the muscle's contractile facility is being used. Because the effects of disuse mimic the dystrophic condition in some ways, it seems logical to assume that the intensity of the contraction of a disused muscle is proportionately greater than that of a normal muscle to achieve or maintain a given tension. And, because previous studies have shown a positive relationship between muscle contraction intensity and muscle fatigue (refs. 34 and 44 to 46), disuse effects could have the propensity for increasing muscle fatigability.

It has been established that inactivity has a deleterious effect on neuromuscular functioning; e.g., reduced activity is associated with alterations in the acetylcholine (ACh) sensitivity of motor end plates (ref. 12). Likewise, changes in biochemical concentrations in muscle can alter ACh sensitivity and muscle function (refs. 47 to 50). Changes in calcium and potassium concentrations in the medium surrounding muscle fiber membranes, for example, cause changes in membrane potential and sensitivity; i.e., a reduction in calcium and potassium is accompanied by increased excitability and thus a greater frequency of impulse propagation (refs. 10 and 51). In weightlessness, the neuromusculoskeletal system is influenced by both kinds of effects; however, the exact relationship between them is not known. Lomo et al. (ref. 37) have proposed that the main role of the nerve in controlling chemosensitivity of the muscle membrane is its ability to maintain muscular activity. This suggests, then, that inactivity is the principal factor contributing to the dysfunction characteristics of the space-flight disused muscle. If this suggestion is correct, then an appropriate in-flight exercise program should alleviate the muscle problem. Conversely, if it is not correct, then an exercise program may have only short-term beneficence.

The proper functioning of skeletal muscle is also dependent on an adequate flow of blood to the muscle. For example, it is known that if the blood supply to an exercising muscle is occluded, fatigue occurs sooner than if the circulation is normal (refs. 52 to 55). Also, it is known that both isometric and isotonic muscle contractions may occlude arterial flow by means of intramuscular pressure.

Cardiovascular and pulmonary changes, as well as a general deconditioning of the cardiopulmonary system, have occurred during space flight (ref. 57). A general deconditioning sufficient to affect blood flow to skeletal muscles during various levels of muscle contraction could have deleterious effects on the functional attributes of the muscle.

Future space-flight research on muscle function should include studies designed to answer the types of questions presented in this report. Studies to determine the etiology of both nerve and muscle in neuromuscular system dysfunction attributable to weightlessness and to investigate the practical consequences of space-flight muscle dysfunction to work performance capability should also be included.

CONCLUSIONS

The skeletal muscle changes of the U.S. crewmembers of the Apollo-Soyuz crew have been recorded. The objective was to assess skeletal muscle changes that might occur in response to a relatively short period of weightlessness, i.e., less than 10 days. The muscles measured were the gastrocnemius, the soleus, the biceps brachii, and the brachioradialis. Both integration and frequency analyses were performed on the recorded electromyograms of only one crewman because toxic gas exposure precluded further postflight testing of the other crewmen. The following changes were noted.

1. Muscle excitability, i.e., frequency of impulse propagation, was increased as evidenced by a significant shift of the predominant firing frequency into higher frequencies. For example, in the gastrocnemius, there was a shift of approximately 25 percent of base level and in the biceps brachii, approximately 40 percent of base level.

2. Muscle electrical efficiency, as measured by the ratio of electrical activity to unit of force, was found generally to decrease as a result of the 9 days of weightlessness. However, the efficiency of the biceps brachii was increased after the period of weightlessness. The implications of this finding are discussed.

3. Fatigability of the postflight muscles was significantly increased, as evidenced by a shift of spectral power into the lower frequencies as a result of the relative disuse during weightlessness.

4. The antigravity muscles in the legs appear to be most affected by the period of weightlessness. This may be inherent in the muscles or may be a result of less effective in-flight exercise.

5. It is concluded that the disuse effects of weightlessness on skeletal muscles are precipitated early in the period of weightlessness and, based on results of a more lengthy period of weightlessness (second manned Skylab mission), gradually increase in severity as the weightlessness continues. Additional research is required to determine the practical implications of these findings and their ultimate consequences for missions of 1 to 3 years' duration.

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, March 24, 1976
966-60-00-00-72

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TABLE I.- T-TESTS FOR SIGNIFICANCE OF POSTFLIGHT SHIFTS IN SPECTRAL POWER FOR THE GASTROCNEMIUS AND BICEPS BRACHII

[30 percent MVC for 10 seconds]

Muscle	Postflight shift	
	Low hertz	High hertz
Gastrocnemius	[a]2.43	-0.84
Biceps brachii	1.20	[a]-3.18

[a] $p < 0.05$ (one-tailed test).

TABLE II.- SUMMARIES OF THE ANALYSES OF VARIANCE OF MUSCLE DATA

Source of variation	Degrees of freedom	Mean square	Value of F	p
Gastrocnemius				
Conditions	1	396.1	12.4	<0.05
Time increment (fatigue index)	1	1170.5	36.7	<.01
Frequency bands	4	250.3	7.8	<.05
Conditions X time	1	974.3	30.5	<.01
Conditions X frequency	4	105.9	3.3	NS[a]
Time X frequency	4	41.8	1.3	NS
Error	4	31.9		
Total	19			
Soleus				
Conditions	1	82.4	26.6	<0.01
Time increment (fatigue index)	1	1538.3	496.2	<.01
Frequency bands	4	238.0	76.8	<.01
Conditions X time	1	188.5	60.8	<.01
Conditions X frequency	4	45.4	14.7	<.05
Time X frequency	4	63.0	20.3	<.01
Error	4	3.1		
Total	19			

[a] Not significant.

TABLE II.- Concluded

Source of variation	Degrees of freedom	Mean square	Value of F	p
Biceps brachii				
Conditions	1	2.7	<1	NS
Time increment (fatigue index)	1	305.0	29.3	<0.05
Frequency bands	2	318.0	30.6	<.05
Conditions X time	1	3.5	<1	NS
Conditions X frequency	2	13.8	1.3	NS
Time X frequency	2	92.7	8.9	NS
Error	2	10.4		
Total	11			
Brachioradialis				
Conditions	1	105.0	<1	NS
Time increment (fatigue index)	1	55.9	<1	NS
Frequency bands	2	1088.0	1.7	NS
Conditions X time	1	58.5	<1	NS
Conditions X frequency	2	30.1	<1	NS
Time X frequency	2	335.7	<1	NS
Error	2	640.9	<1	NS
Total	11			

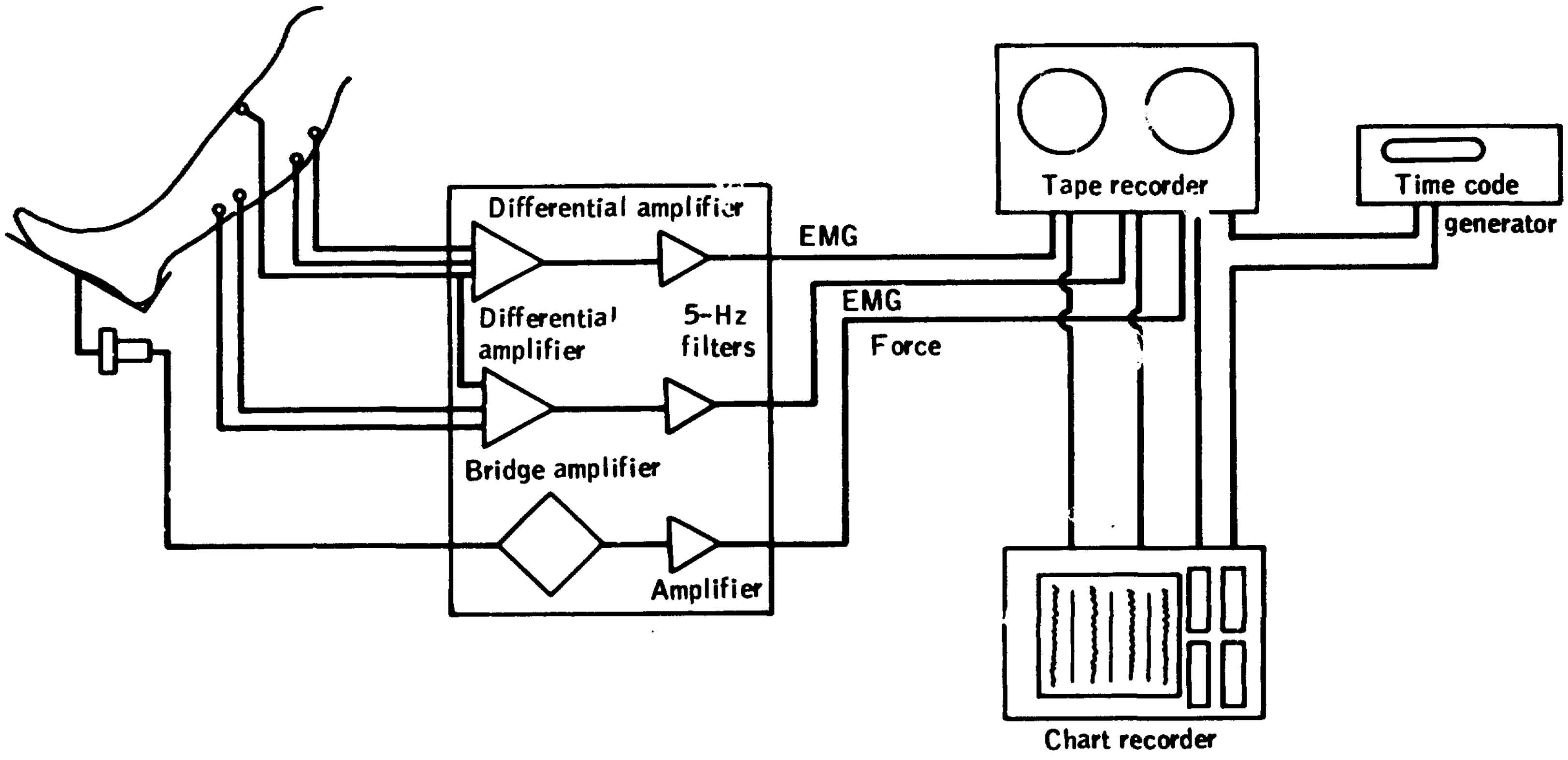
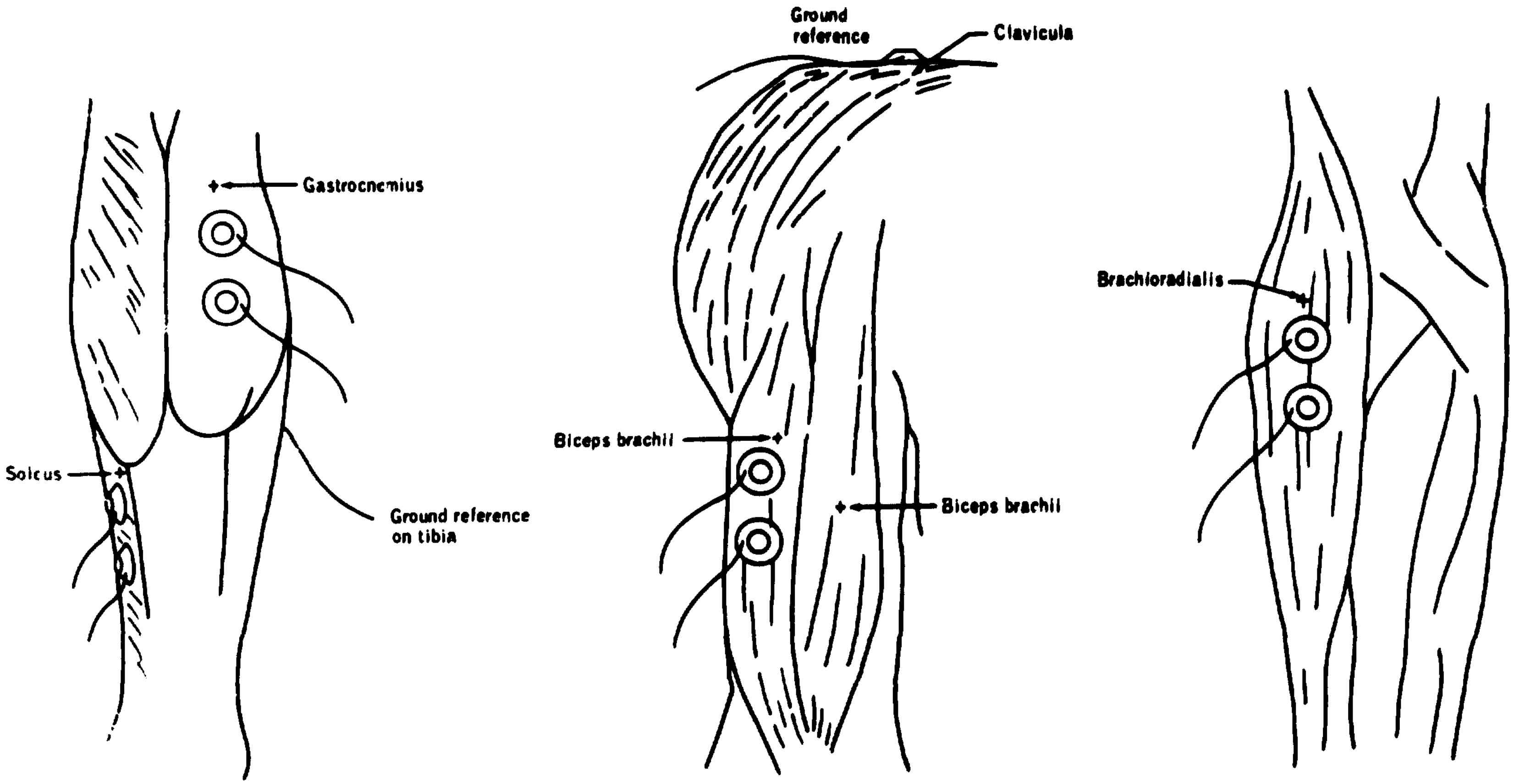


Figure 1. · Experimental configuration.

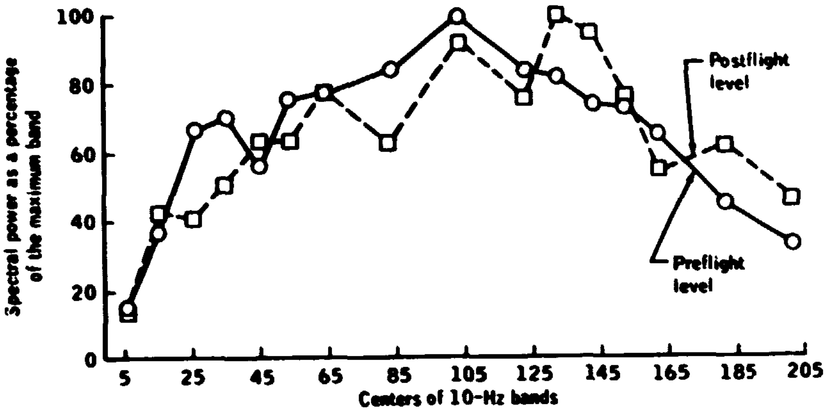


leus and gastrocnemius.

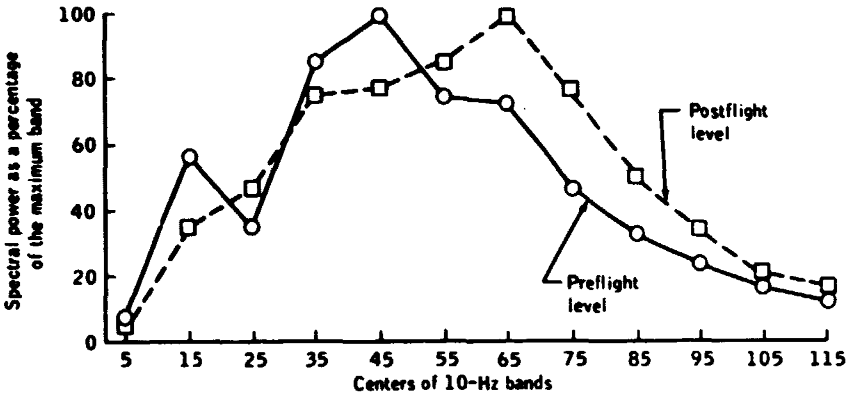
(b) Biceps brachii and ground reference.

(c) Brachioradialis.

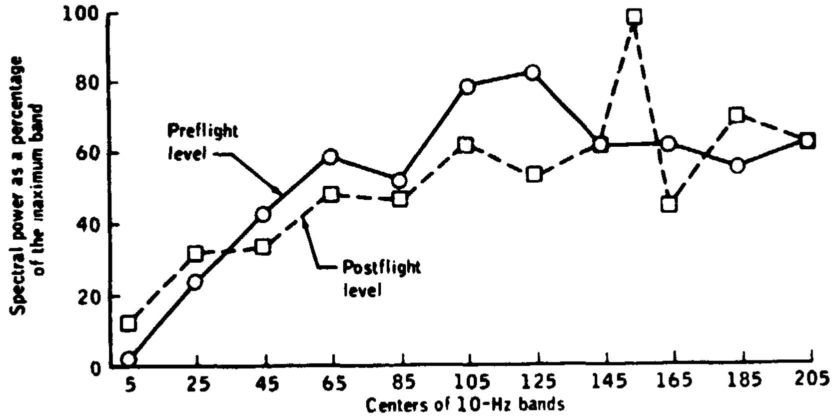
Figure 2.- Positions of surface electrodes on muscles.



(a) Gastrocnemius.

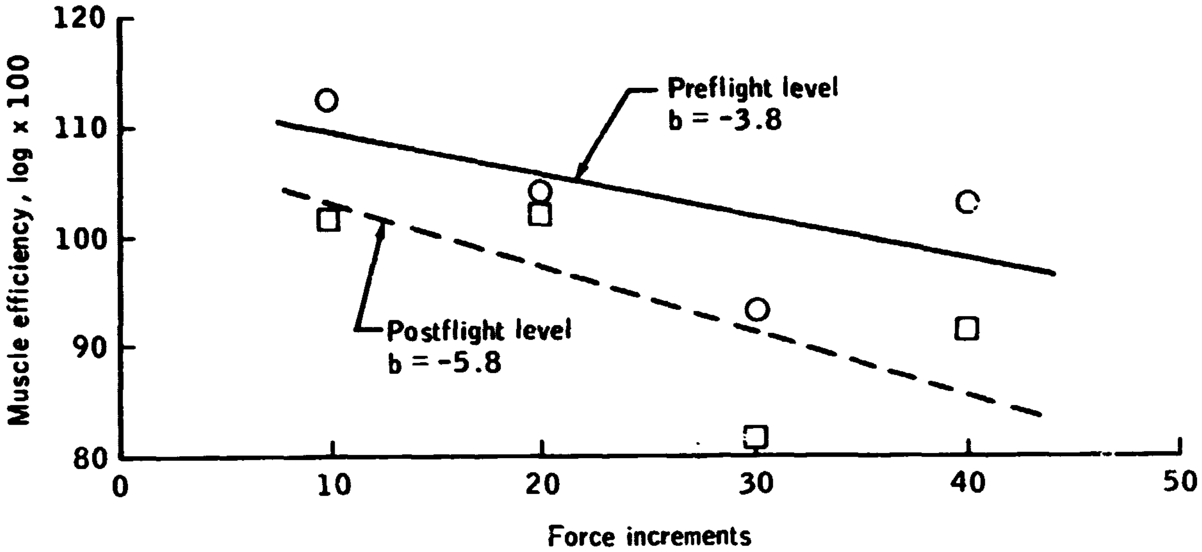


(b) Biceps brachii.

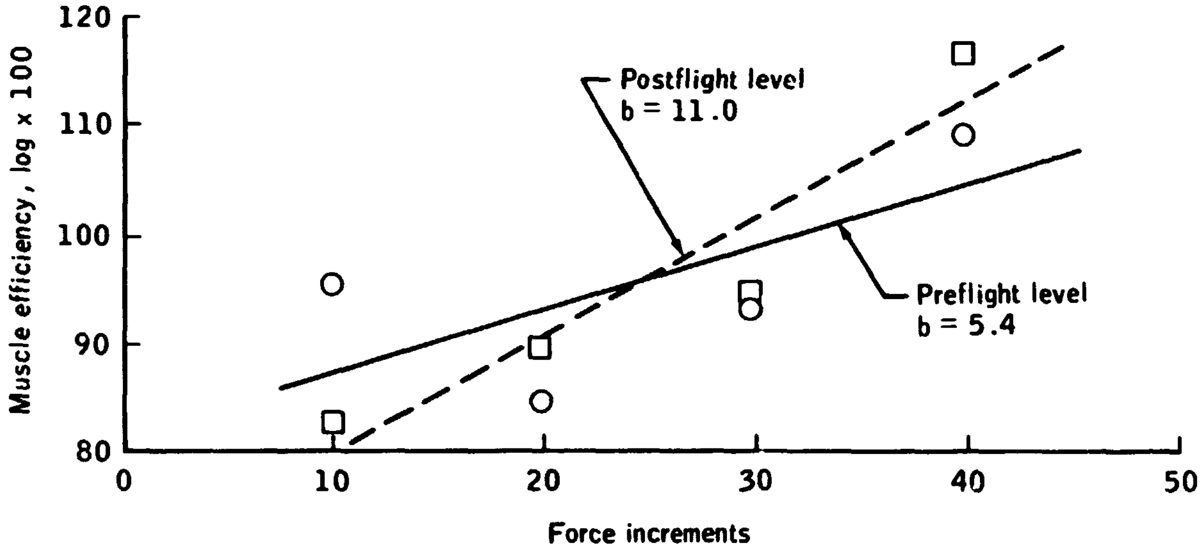


(c) Soleus.

Figure 3.- Preflight and postflight distributions of muscle spectral power stressed at 30 percent MVC.

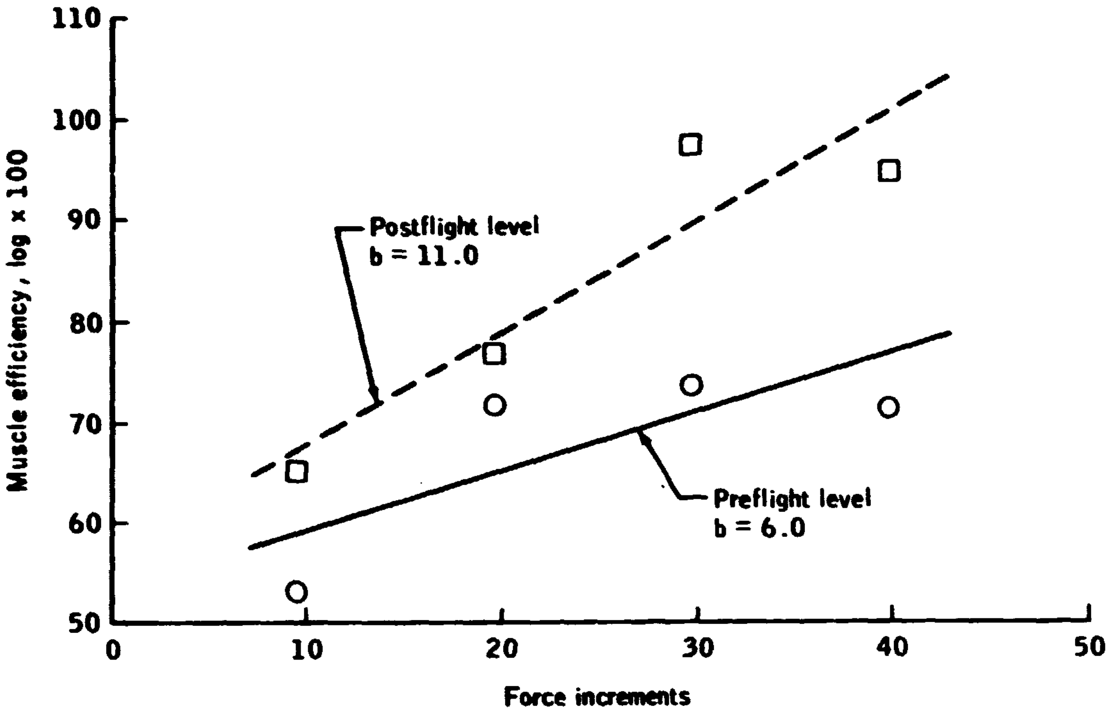


(a) Gastrocnemius.

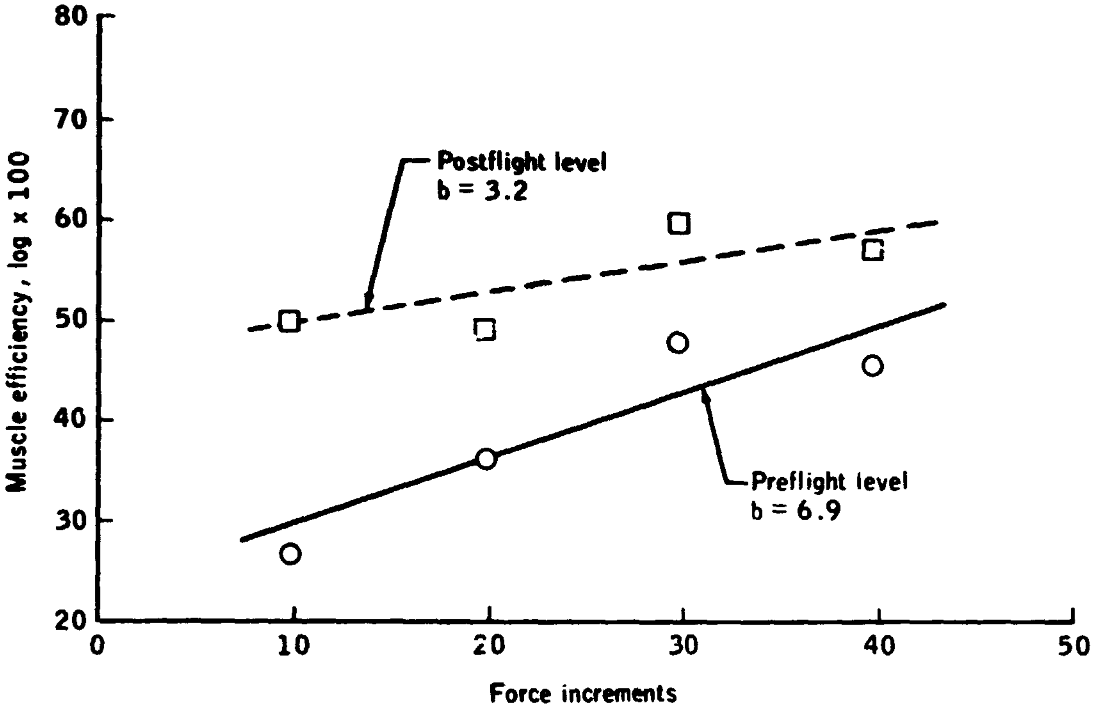


(b) Soleus.

Figure 4.- Plots of muscle electrical efficiency data showing preflight and postflight levels and slopes for the force increments of 10, 20, 30, 40, and 50 percent MVC tests (b = slope coefficient).

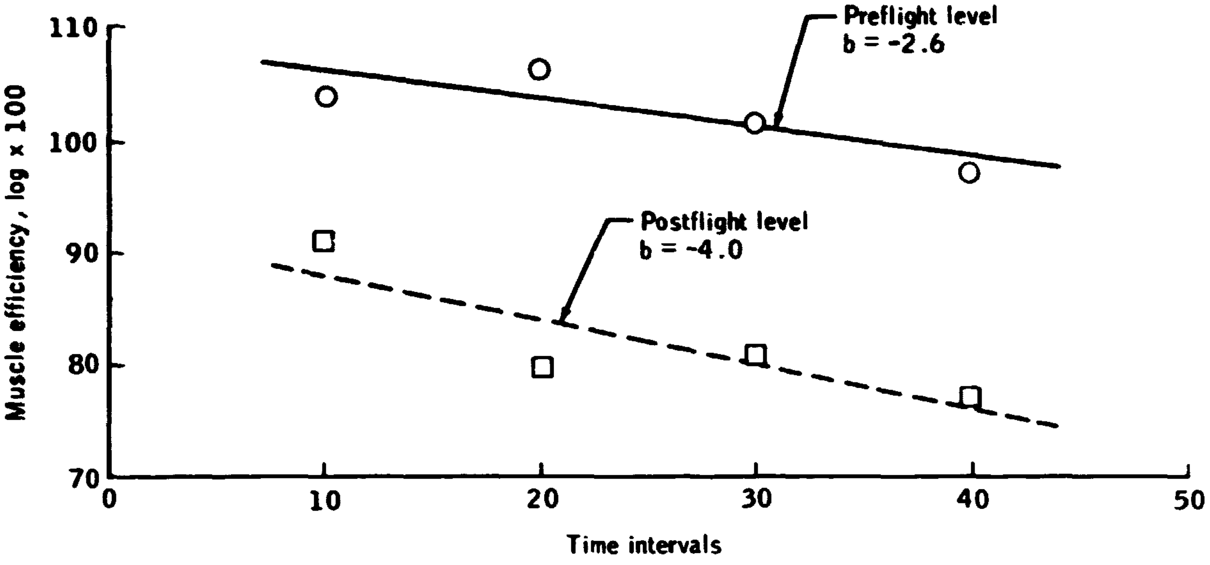


(c) Biceps brachii.

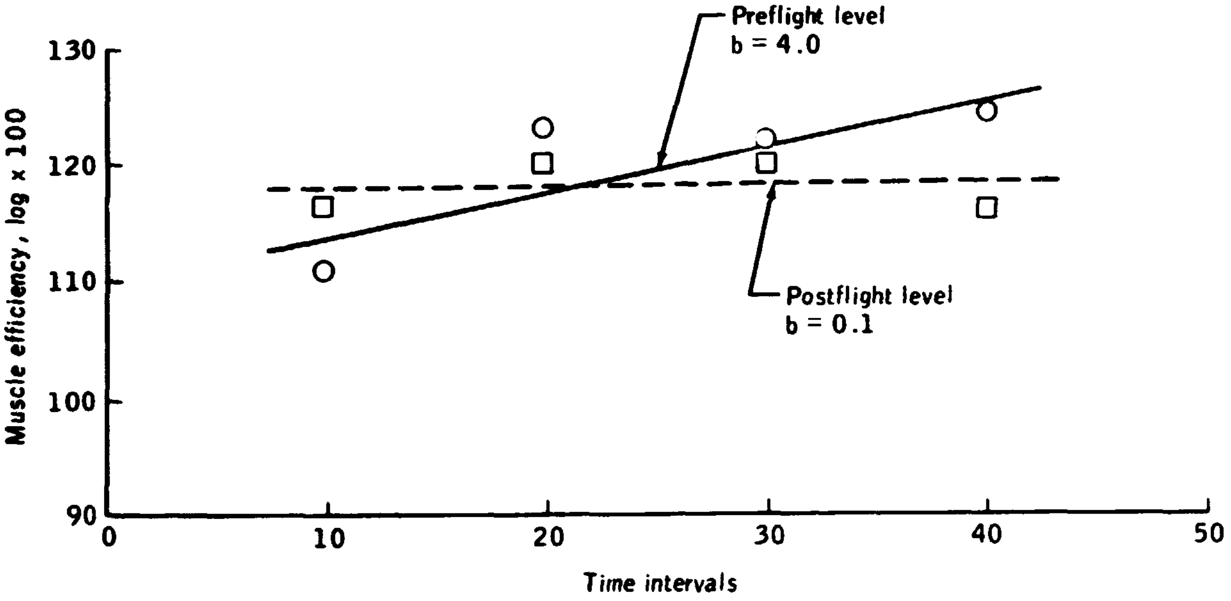


(d) Brachioradialis.

Figure 4.- Concluded.

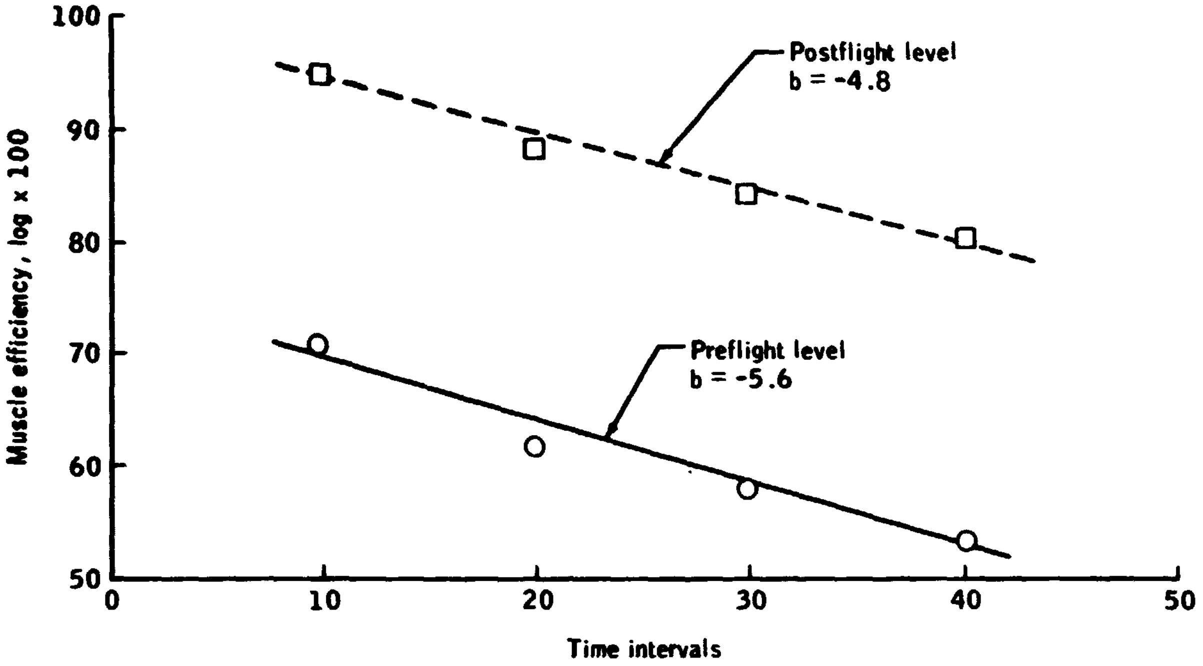


(a) Gastrocnemius - 50 percent MVC.

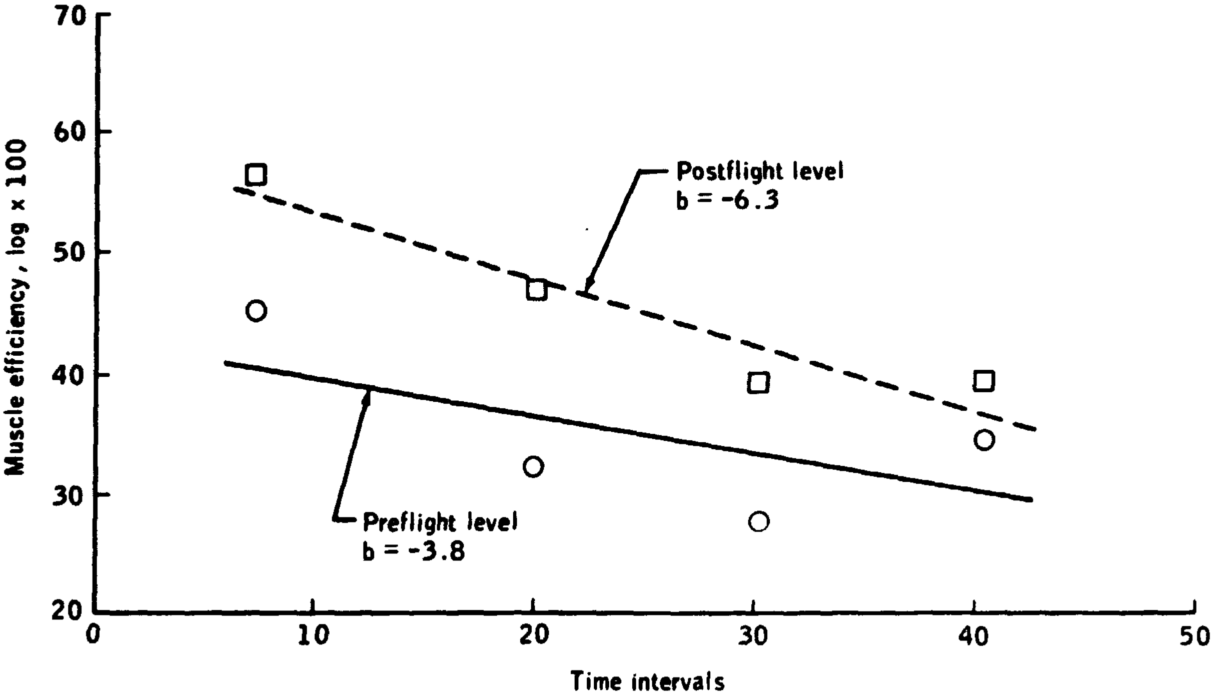


(b) Soleus - 50 percent MVC.

Figure 5.- Plots of muscle electrical efficiency data during 1-minute isometric stress showing preflight and postflight levels and slope coefficients (b).

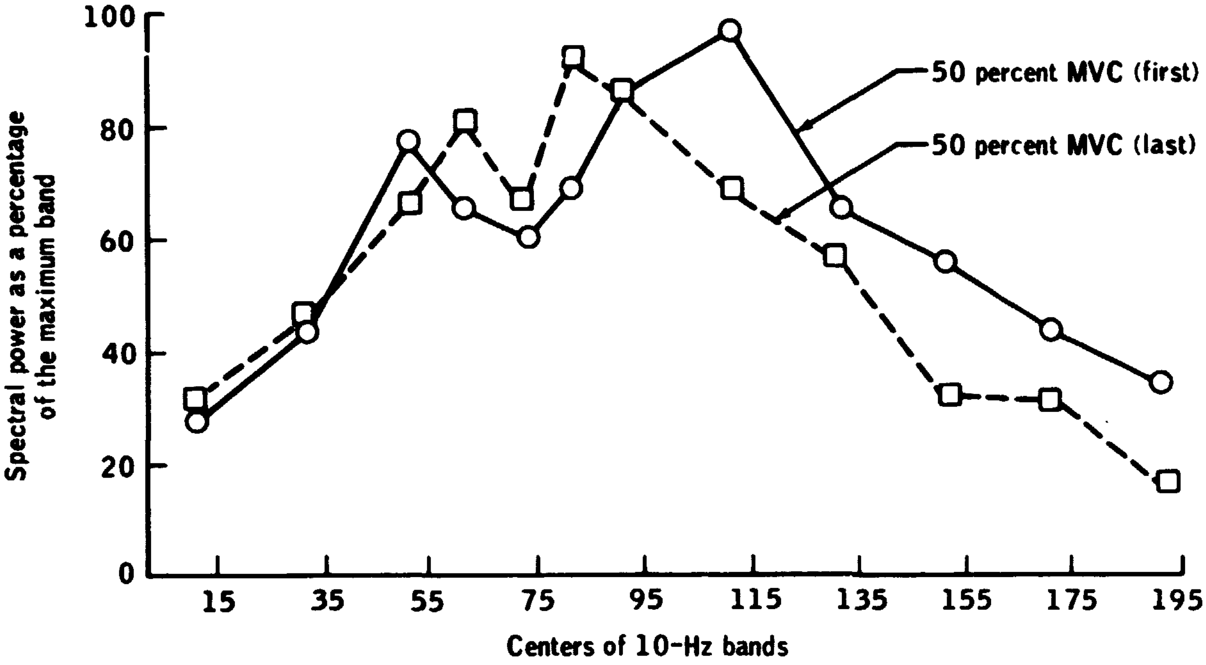


(c) Biceps brachii - 40 percent MVC.

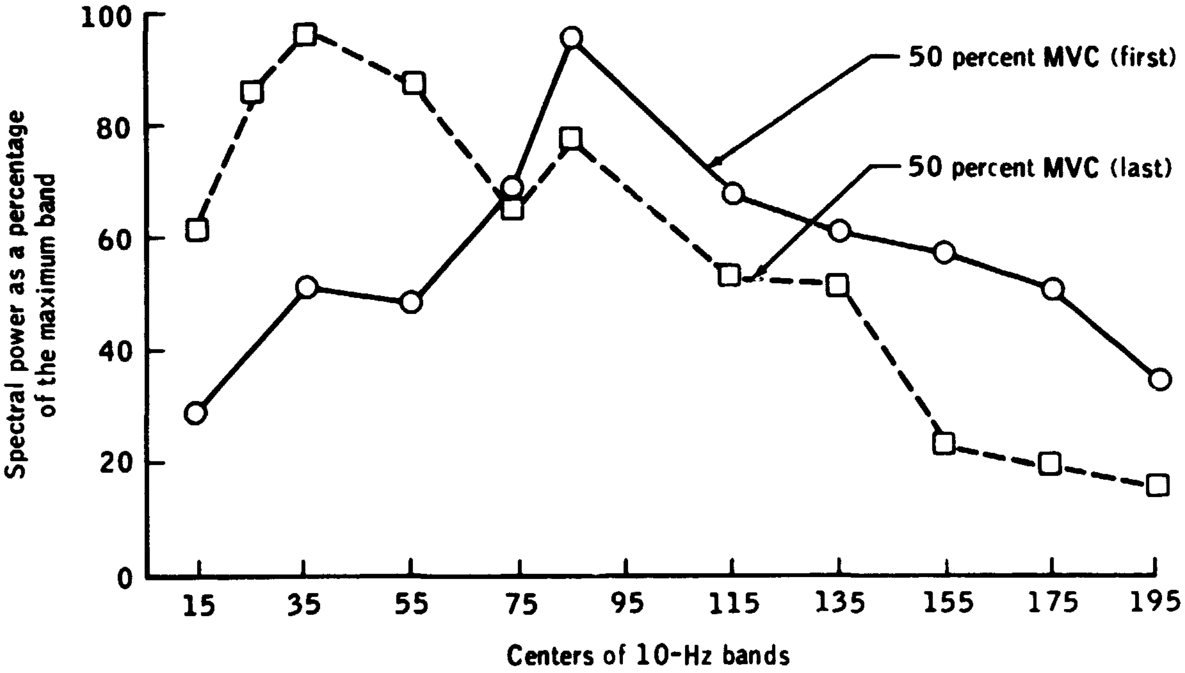


(d) Brachioradialis - 40 percent MVC.

Figure 5.- Concluded.

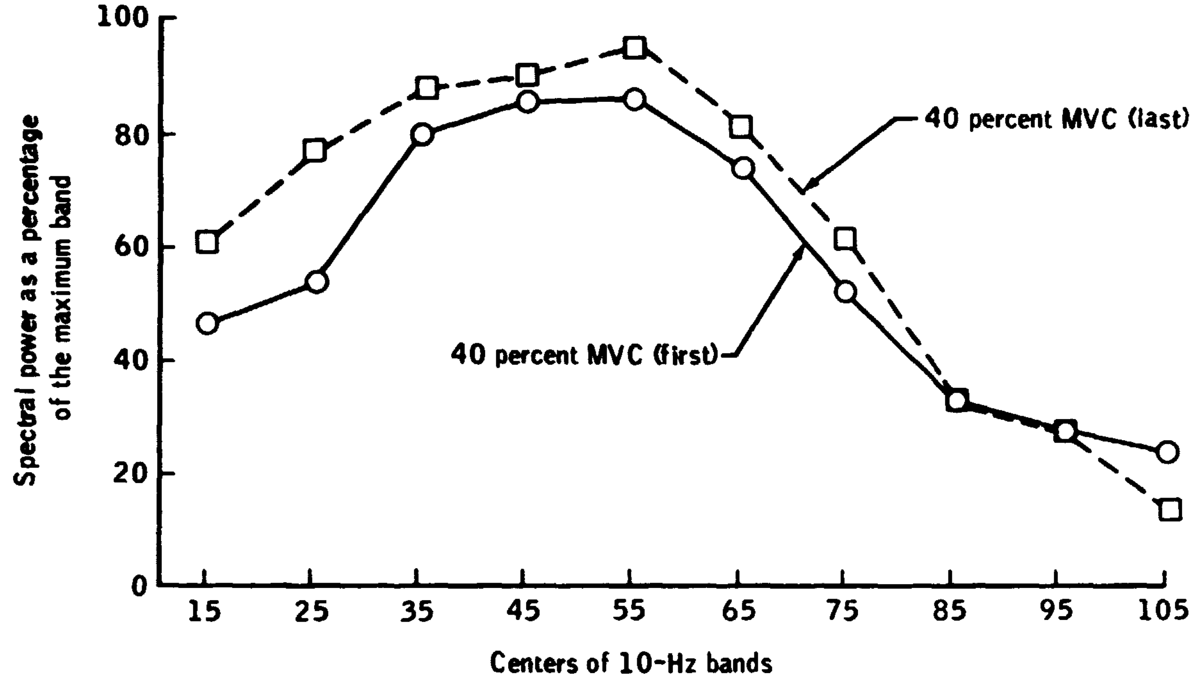


(a) Preflight data.

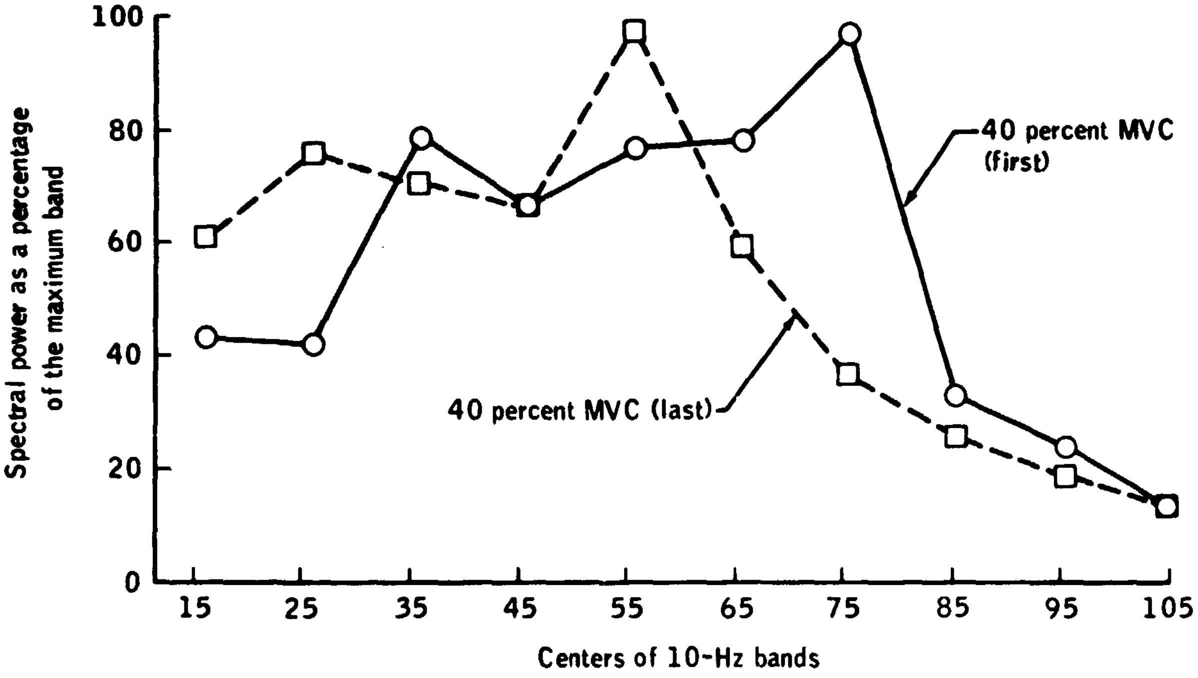


(b) Postflight data.

Figure 6.- Plots of fatigue data for the gastrocnemius showing spectral power shifts resulting from the 1-minute isometric stress.

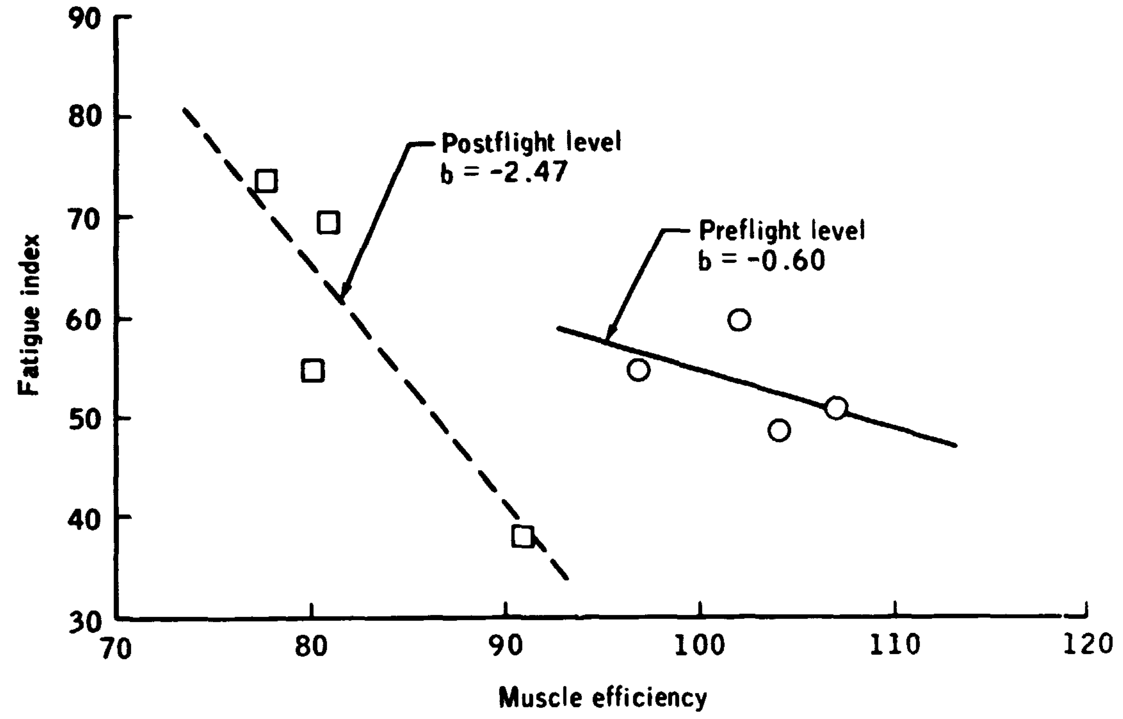


(a) Preflight data.

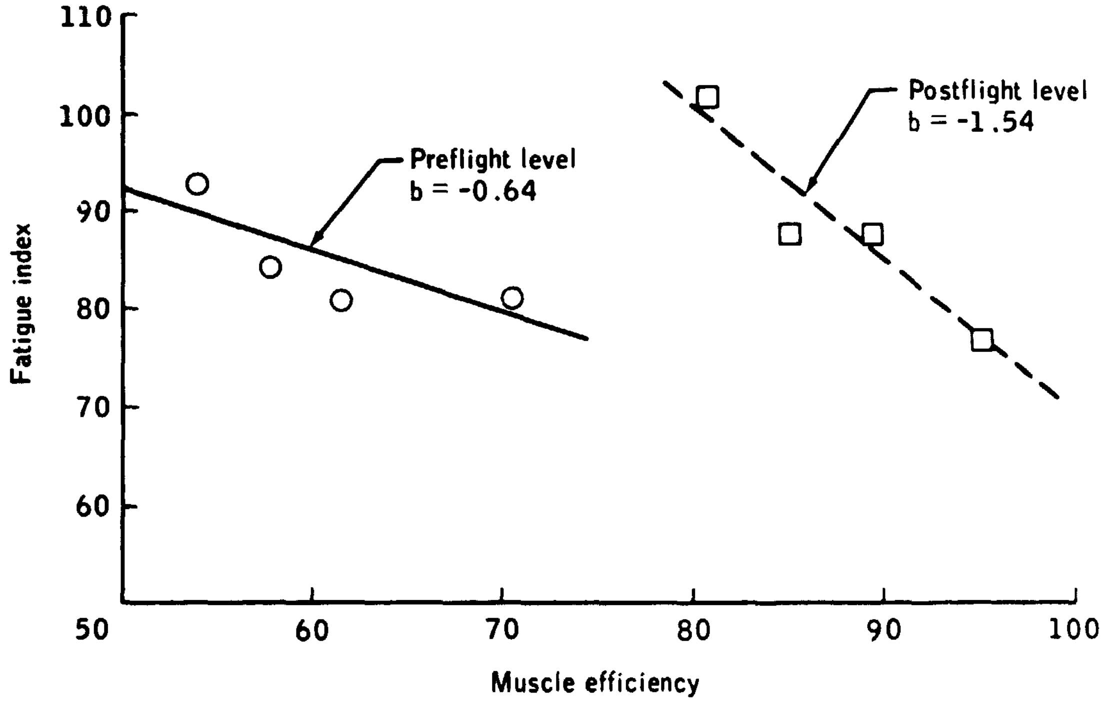


(b) Postflight data.

Figure 7.- Plots of fatigue data for the biceps brachii showing spectral power shifts resulting from the 1-minute isometric stress.



(a) Gastrocnemius.



(b) Biceps brachii.

Figure 8.- Plots of muscle electrical efficiency as opposed to spectral power index of fatigue (b = slope coefficient).